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BIAXIAL TENSILE BEHAVIOR OF Ti-5Al-2.5Sn ALLOY

TECHNICAL REPORT

by

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JUNE 1967

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U. S. ARMY MATERIALS RESEARCH AGENCY
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ABSTRACT

The elastic and plastic tensile properties of two sheets of 5Al-2.5Sn titanium alloy were determined. The effect of various annealing temperatures up to 1900 F on these properties were obtained on one sheet. Two closed-end cylindrical pressure vessels which had reduced wall thicknesses away from the longitudinal and circumferential welds were fabricated from each sheet. Two of the pressure vessels from one sheet exhibited yield improvements which were slightly lower than those predicted by the Hill-Backofen anisotropic yield criterion. The other two vessels yielded at less than that predicted by the Von Mises yield criterion. All vessels exhibited exceptionally high burst strengths as compared to the uniaxial tensile strengths.

CONTENTS

INTRODUCTION

Considerable research and testing has been conducted on orientation and textural behavior of metals. Recently, a concentrated effort has been devoted to alpha and weakly stabilized alpha-beta titanium sheet alloys because of their tendency to develop strong crystallographic textures under certain rolling conditions. These titanium alloys have a hexagonal close-packed crystal structure (alpha phase) and the basal plane tends to be alined in the plane of the sheet. Backofen has extended Hill's plasticity theory[1] which predicts significant yield strength improvements under a biaxial stress field for sheet materials which develop this type of texture. This yield equation, which relates the conventional uniaxial yield strength (X_o), the anisotropy parameter (R*), and the principal biaxial stresses (σ_x, σ_y), is:

$$\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y \left[\frac{2R}{1+R}\right] = X_o^2. \tag{1}$$

For the case of non-rotational symmetry (i.e., the transverse strain ratio R_T is not equal to the longitudinal strain ratio R_L), Equation 1 takes the following form:

$$\sigma_x^2 + \frac{(R_L+1)R_T}{(1+R_T)R_L}\sigma_Y^2 - \frac{2R_T}{1+R_T}\sigma_x\sigma_y = X_o^2 . \tag{2}$$

In a long, thin-walled, closed-end cylindrical pressure vessel ($\sigma_x = 2\sigma_y$), Equations 1 and 2 reduce to the following:

$$\frac{\sigma_x}{X_o} = \sqrt{\frac{4(1+R)}{5+R}}, \tag{3}$$

$$\frac{\sigma_x}{X_o} = \sqrt{\frac{4(1+R_T)R_L}{4R_L+R_LR_T+R_T}}. \tag{4}$$

Equation 4 has been plotted in Figure 1 for values of R_L and R_T between 1 and 12. In addition, the case where $R_L = R_T$ (rotational symmetry) has also been plotted in this figure. Maximum strengthening occurs in a 2 to 1 stress field when $R_T = R_L$ or for the case of rotational symmetry. It is evident in Figure 1 that the slopes of the curves decrease with increases in R values, and for values greater than 6, little additional strengthening is predicted.

A great deal of effort has been devoted to both the macro-mechanics[1] (Backofen) and the micro-mechanics[2] (Larson) approaches to develop a theoretical analysis for texture-hardening materials. In addition, testing techniques have been developed[3] to measure the elastic and plastic tensile strain properties to characterize the state of anisotropy. The engineering practicality of using these materials in closed-end cylindrical pressure vessels[1,4-6] to provide biaxial yield strength improvements has been stated many times. To demonstrate this improvement, a closed-end cylindrical pressure vessel

*$R = \Delta\epsilon_w/\Delta\epsilon_t$. *This is the ratio of the rate of change of the width-to-thickness plastic strain.*

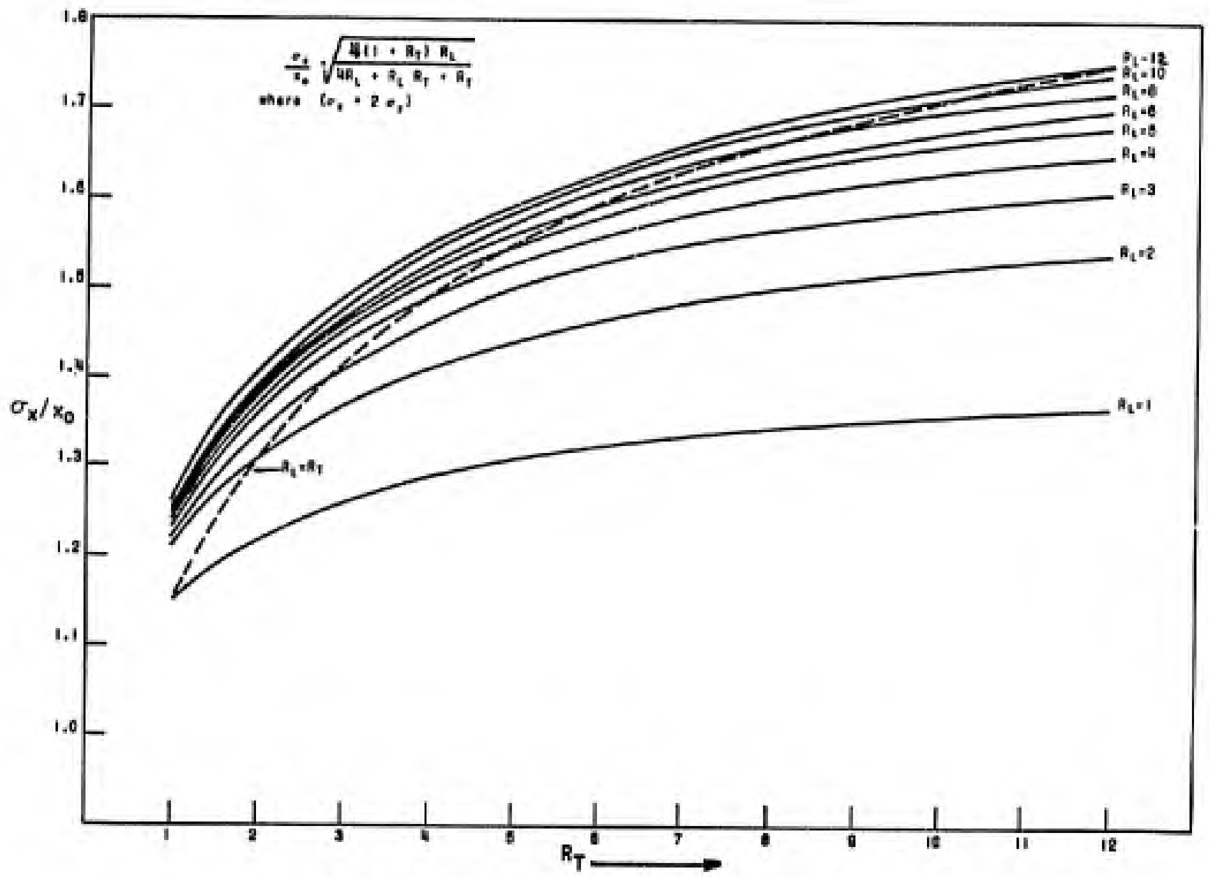


Figure 1. ANISOTROPIC YIELD EQUATION

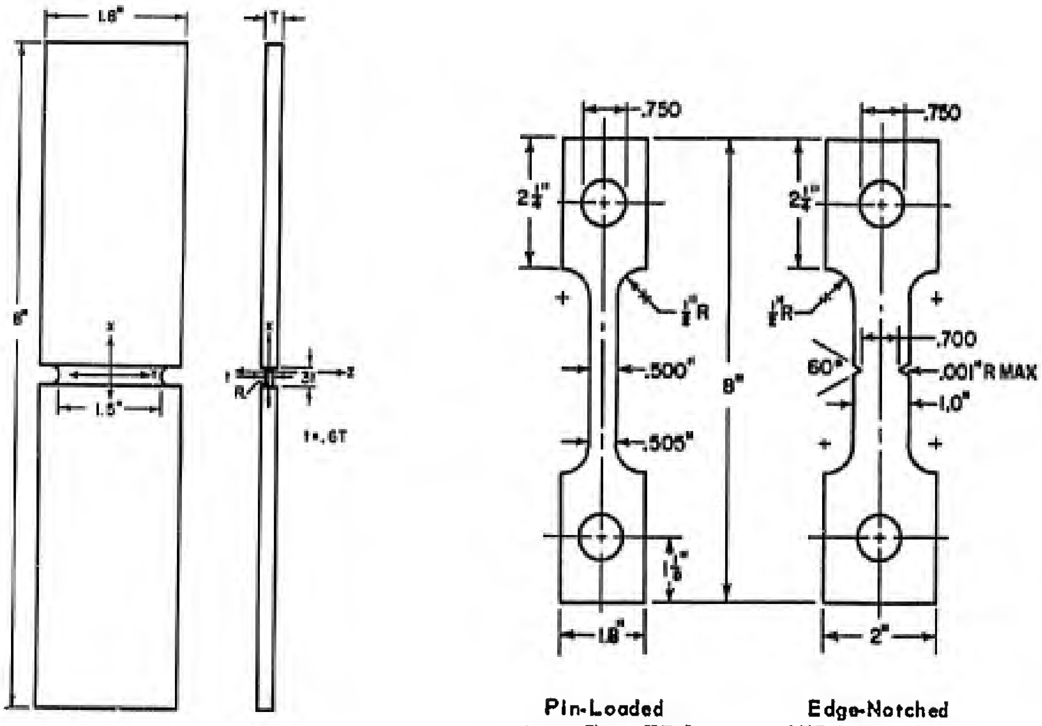
which will not fail in the longitudinal weld[4] must be manufactured from sheet materials on which both the elastic and plastic properties have been determined. The purpose of this study was to fabricate such pressure vessels and to compare these results with those predicted by the Hill-Backofen yield theory.

MATERIALS

Two sheets, 0.125 inch X 36 inches X 96 inches, of annealed Ti-5Al-2.5Sn of extra low interstitial grade were obtained for this study. These sheets have been designated as A and B in this report.

EXPERIMENTAL PROCEDURE

Plane strain biaxial tensile specimens (AMRA Type TF-26), pin-loaded flat tensile specimens (AMRA Type TF-14), and edge-notched flat tensile specimens (AMRA Type TF-18) were employed in these evaluations. The dimensions of the test specimens are presented in Figure 2. Conventional wedge-type grips were used in testing the biaxial tensile specimens.



Plane Strain Biaxial Tensile Specimen
AMRA Type TF-26

Pin-Loaded
AMRA Type TF-14

Edge-Notched
AMRA Type TF-18

Flat Tensile Specimens

Figure 2. SHEET TENSILE TEST SPECIMENS

Adjustments had to be made in the testing speeds because there is an order of magnitude difference in the gage lengths between the biaxial and uniaxial test specimens. To minimize this strain rate effect, head speeds of 0.02"/min and 0.005"/min were employed in testing the uniaxial and biaxial tensile specimens to fracture.

The elastic and plastic strain properties were determined by use of 90-degree rosette foil gages (FAB X-12-12), attached to the center of the flat tensile specimens. The width strain (ε_W) and the load were recorded continuously as a function of the longitudinal strain (ε_L) on an Electro-Instruments X-Y-Y' recorder. In addition to the strain gage reading, an extensometer was attached to each specimen. A typical recording and sample calculation are presented in Figure 3.

Two longitudinal and transverse tensile and biaxial tensile specimens were machined from both sheet A and B and tested in the mill-annealed condition. A series of annealing cycles were conducted on specimens from sheet A to determine the effects upon the tensile and strain properties.

Two transverse tensile and notch tensile specimen blanks were machined from each sheet and were welded, using the same technique as that used to fabricate the pressure vessels.

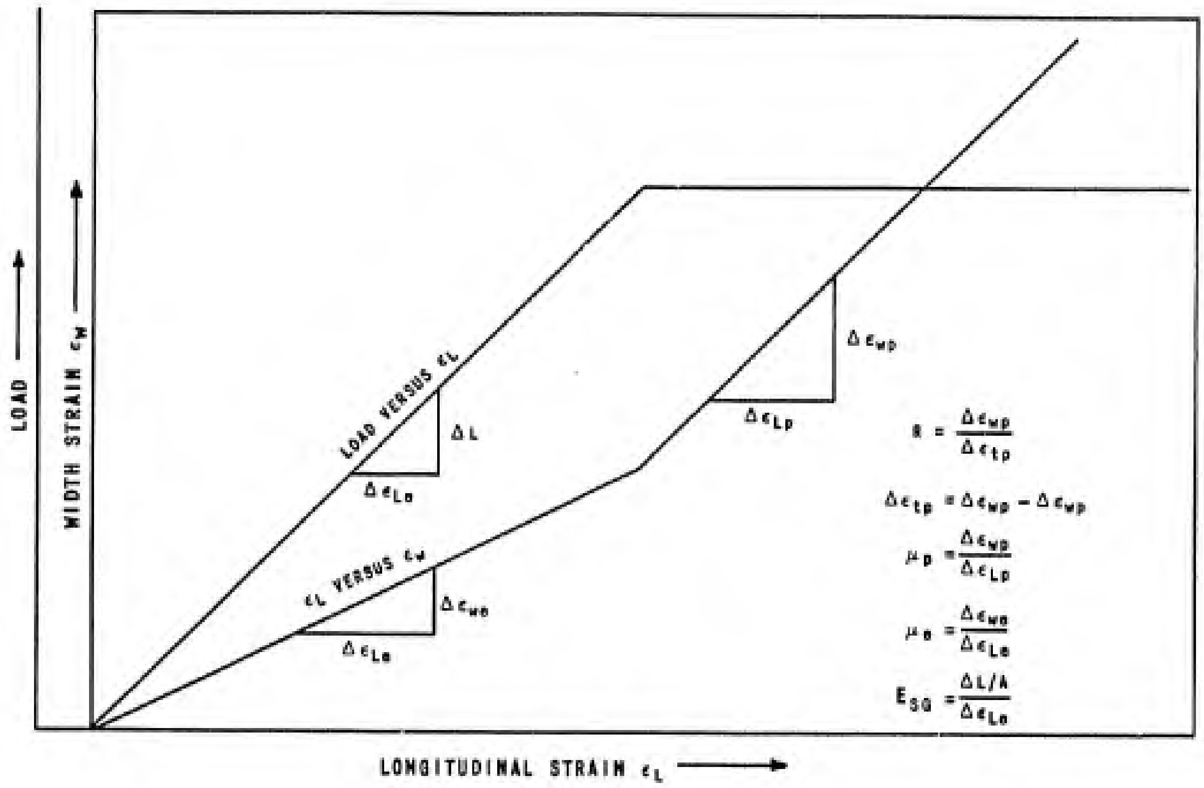


Figure 3. TYPICAL LOAD STRAIN AND STRAIN-STRAIN CURVE

Two 6-inch-diameter, 24-inch-long, closed-end cylindrical pressure vessels were fabricated from each sheet. The transverse sheet direction was oriented in the hoop direction on the pressure vessels. These pressure vessels were formed at room temperature using a break press, since excessive spring back was encountered using available roll-forming equipment. All welding was performed using electron-beam techniques and were X-ray inspected. The entire cylinder received an annealing treatment of 1000 F for 2 hours, followed by an air cooling after assembly.

The cylinders were then set up on a tracer lathe. The outside diameter and the longitudinal profile were reduced, as indicated in Figure 4. Ultrasonic thickness measurements were provided with each vessel.

Strain gages (FAB X-12-12), 90-degree foil rosettes, were attached to the cylinders at approximately mid-length and 180 degrees from the longitudinal weld. A second rosette gage was located either near the weld or where the thickness gage readings indicated a thin portion in the wall. The position of the gages diameter, and thickness of the cylinders (measured with a micrometer after burst) are summarized in Table I.

The cylinders were positioned horizontally on V-blocks and loaded hydrostatically, using high-pressure tubing connected to one end.

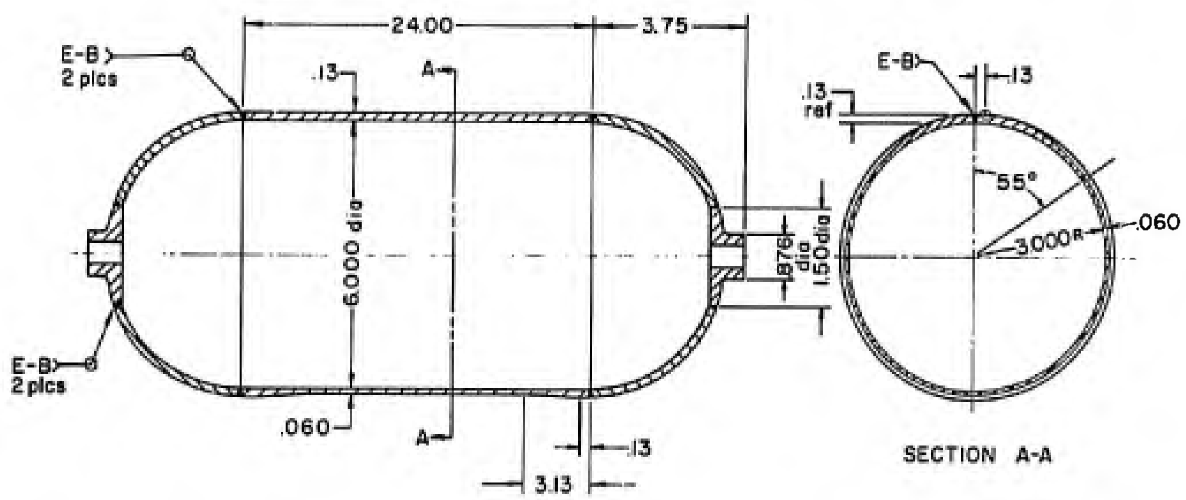


Figure 4. TITANIUM PRESSURE VESSEL ASSEMBLY

Prior to pressurizing for testing, the cylinders were loaded and unloaded until the strain gages re-zeroed without any set. The cylinders were then loaded hydraulically and the strain gage outputs were recorded for increments of load, using a Baldwin switching and balancing unit and an SR-4 indicator. Strain readings were recorded up to the pressure at which the indicator could not be balanced. The vessels were then unloaded and reloaded at a uniform rate until burst.

Table I. PRESSURE VESSEL DIMENSIONAL DATA

Property	Pressure Vessel Number			
	1A	2A	1B	2B
Distance from forward weld to gage 1 (inches)	14-1/4	11-5/8	11-1/8	12-3/4
Position from weld gage 1 (degrees)	180	160	185	150
Distance from forward weld to gage 2 (inches)	17-1/4	15-7/8	15-5/8	17-3/4
Position from weld gage 2 (degrees)	47	43	155	85
Thickness at gage 2 (inches)	0.068	0.068	0.067	0.074
Distance from forward weld to origin of fracture (inches)	8	14	7-1/2	10
Thickness at fracture (inches)	0.045	0.052	0.048	0.052
Diameter at fracture (inches)	6.08	6.09	6.06	6.04
Diameter at gage 1 (inches)	6.10	6.08	6.05	6.08

RESULTS AND DISCUSSION

The sheet tensile data obtained for the conditions evaluated are summarized in Tables II and III. The elastic and plastic tensile properties and the plane strain biaxial tensile values for the various annealing cycles obtained on sheet A are presented in Table IIa. The yield strength, ultimate tensile strength, and plane strain biaxial tensile strength decreases as the annealing temperature is increased above 1000 F.

Table II. ELASTIC AND PLASTIC TENSILE PROPERTIES OF Ti-5Al-2.5Sn

Treatment	Direction	μ_e	μ_p	R	E_{SG} (psi)	Y.S. 0.1% (ksi)	U.T.S. (ksi)	BTS	Biaxial Tensile Ratio BTS/UTS (avg)	Biaxial Tensile Ratio Calc.*
a. Sheet A										
Mill-Annealed	T	0.385 0.383	0.680 0.694	2.36 2.25	17.7×10^6 17.4	109.9 110.1	116.5 115.7	157.1 180.3	1.45	1.40
	L	0.367 0.350	0.692 0.656	2.12 1.92	16.1 16.5	106.0 105.8	120.1 121.1	156.4 170.5	1.36	1.34
800 F 2 hr AC	L	0.375 0.371	0.695 0.716	2.16 2.52	17.2 17.1	111.0 109.0	122.6 121.7	179.9 184.1	1.49	1.40
1000 F 2 hr AC	L	0.375 0.384	0.727 0.710	2.66 2.42	16.3 17.1	110.5 111.0	120.0 122.2	182.2 180.7	1.50	1.44
	T	0.386 0.384	0.700 0.700	2.64 2.33	18.1 18.2	113.0 114.0	117.5 119.0	- -	-	-
1300 F 4 hr AC	L	0.372 0.375	0.740 0.805	2.86 4.13	17.0 17.2	101.5 100.5	113.0 111.0	170.7 169.8	1.54	1.56
1500 F 1/4 hr AC	L	0.374 0.372	0.740 0.772	2.82 2.33	16.0 16.5	103.0 100.3	110.4 110.4	139.9 137.1	1.28	1.45
1500 F 1/2 hr AC	L	0.380 0.389	0.755 0.790	3.10 3.72	16.8 17.0	100.5 99.5	110.0 111.0	172.2 146.2	1.43	1.57
1600 F 1/4 hr AC	L	0.372 0.375	0.704 0.726	2.50 2.66	16.6 16.6	101.5 100.0	109.6 109.8	142.5 141.6	1.30	1.44
1700 F 1/4 hr AC	L	0.366 0.373	0.683 0.690	2.16 2.22	16.4 16.4	100.2 100.4	109.7 109.3	144.6 127.8	1.24	1.32
1800 F 1/4 hr AC	L	0.382 0.374	0.733 0.694	2.75 2.28	17.2 17.?	95.3 96.7	107.3 107.8	135.2 140.3	1.27	1.42
1900 F 1/4 hr AC	L	0.272 0.304	0.493 0.448	0.97 0.82	17.6 18.3	96.3 98.4	103.3 104.5	105.0 97.8	0.98	1.13
b. Sheet B										
Mill-Annealed	L	0.358 0.364	0.623 0.663	1.56 1.92	17.2 18.4	111.0 108.8	126.0 125.5			
	T	0.400 0.388 0.400 0.388	0.760 0.741 † †	3.20 3.00 - -	17.3 17.7 17.8 16.9	115.2 113.0 111.0 111.0	121.6 120.5 118.0 112.0			

*$\sigma_x/x_o = R+1/\sqrt{2R+1}$

†Strain gages became unbonded before adequate plastic strain values could be recorded.

Table III. TENSILE AND NOTCH TENSILE DATA ON ELECTRON BEAM WELDS
(TRANSVERSE SPECIMENS)

Yield Strength at 0.1% (ksi)	Yield Strength at 0.2% (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Notch Tensile Strength (ksi)	Notch Tensile Strength / Ultimate Tensile Strength
Sheet A					
116.7 115.8	118.3 116.2	120.7 121.0	16.5 17.0	134.5 135.0	1.11
Sheet B					
115.8 117.7	117.1 118.6	122.1 123.9	16.5 18.5	139.1 139.7	1.13

All fractures in base metal.
NASA type notch tensile specimens.
Notch radius 0.001 or less.

There is general agreement between the calculated biaxial tensile ratios* and the measured BTS/UTS ratios. The change in the elastic and plastic strain ratios as well as the biaxial tensile ratios when the material is annealed above the beta transus should be noted. The material becomes nearly isotropic, i.e., R = 1.0.

The actual biaxial tensile ratios measured with the plane strain tensile specimen and those calculated using the Hill-Backofen yield criterion are presented in Figure 5. Data obtained previously on the 6Al-4V and the 4Al titanium alloys are summarized in Table IV and have been included in this figure. The experimental data are in general agreement with the calculated values. However, the values measured with the tensile specimen are ultimate values and the Hill-Backofen criterion is for yielding.

The elastic and plastic properties obtained on sheet B are summarized in Table IIb. This titanium sheet is not as rotational symmetrical as sheet A ($R_L \neq R_T$).

The tensile and notch tensile data obtained in the electron-beam-welded sheet specimens are presented in Table III. These specimens were welded at the center of the gage length on the tensile specimens and across the notch roots on the NASA notch tensile specimens. The high notch tensile strengths and notched-to-unnotched ratio indicate excellent notch toughness.

The strain gage readings obtained for the various internal pressures are presented in Table V and the axial (ε_a) and hoop (ε_h) strain values for the strain gages located near the mid-length of the cylinders are plotted in Figure 6. There is some nonlinearity in the initial portion of the load strain curves. Loading and unloading the cylinders in the elastic region did not eliminate this condition and this could be attributed to the eccentricity

*$\sigma_x/X_o = R + 1/\sqrt{2R+1}$ *and the stress ratio in the specimen is dependent upon the R value,* $\sigma_x/\sigma_y = 1 + 1/R$.

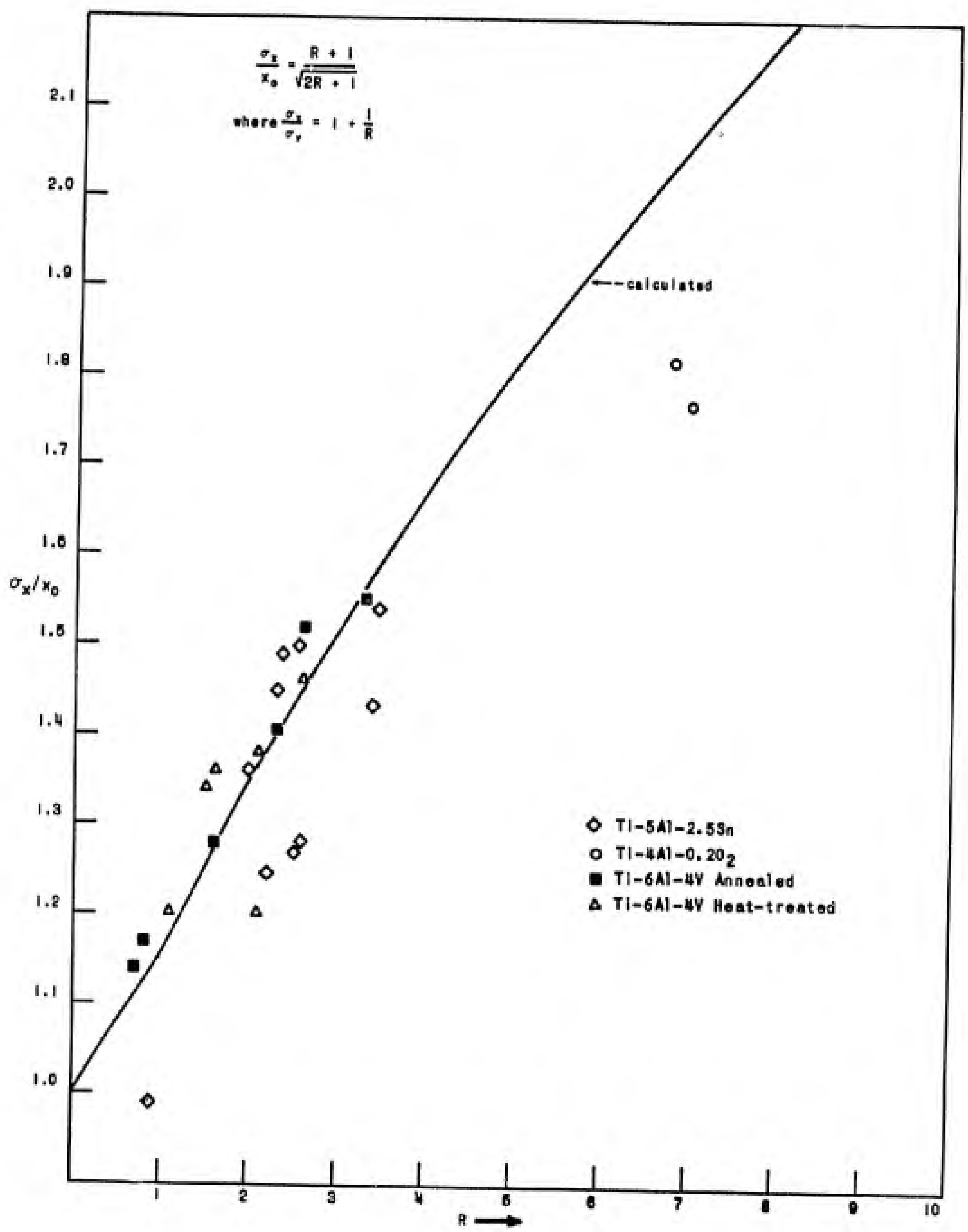


Figure 5. ACTUAL AND CALCULATED PLANE STRAIN TENSILE DATA

Table IV. ELASTIC AND PLASTIC TENSILE PROPERTIES OF ANISOTROPIC SHEET MATERIALS

Treatment	Direction and Mark	Thickness (inch)	Yield Strength at 0.1% (ksi)	Yield Strength at 0.2% (ksi)	Ultimate Tensile Strength (ksi)	R	BTS (ksi)	BTS / UTS
Ti-6Al-4V Alloy								
Annealed	L-1 L-2	0.065 0.065	132.3 131.2	132.6 131.8	140.6 139.4	0.70 0.67	163.7 156.3	1.14
Annealed	T-1 T-2	0.065 0.065	136.5 135.3	136.5 135.3	142.9 141.4	0.67 1.00	155.3 177.5	1.17
Annealed	45-1 45-2	0.065 0.065	130.4 131.3	130.4 131.3	132.1 132.2	1.66 1.67	171.0 168.3	1.28
Annealed	M 71996T	0.060	125.0	-	126.1	3.30	196.6 195.6	1.56
Annealed	M 71996L	0.060	133.6	-	151.4	4.00	-	-
Annealed	L-31	0.125	121.9	121.9	128.2	2.33	176.9 190.5	1.41
Annealed	T-31	0.125	127.3	126.7	129.7	2.62	196.4 196.8	1.52
1500 F 1 hr WQ + 1000 F 3 hrs AC	L-33	0.125	127.7	127.7	143.8	1.60	191.5 198.8	1.36
	T-35	0.125	128.2	129.0	138.9	2.60	200.0 203.9	1.46
1625 F 1 hr WQ + 950 F 3 hrs AC	L-34	0.125	131.5	133.0	149.7	1.50	204.0 195.8	1.34
	T-34	0.125	137.1	137.1	149.0	2.10	204.4 205.9	1.38
1700 F 1 hr WQ + 900 F 3 hrs AC	L-35	0.125	149.7	156.7	172.0	1.10	208.3 206.9	1.20
	T-37	0.125	156.8	161.4	174.2	2.10	208.3 210.3	1.20
Ti-4Al-0.2 O_2								
Annealed	T-41	0.066	96.1	96.8	105.7	6.80	186.6 189.1	1.77
Annealed	L-41	0.066	94.2	94.7	103.2	7.00	187.1 186.1	1.82

of the cylinders. In addition, the outside surface of the cylinders had a machined surface as a result of the technique used for manufacturing the contour. Examination of the strain data on cylinders 1A, 2A, and 2B, those which had strain gages located near the longitudinal weld, indicate very little longitudinal strain. The cylinder which had the two rosette strain gages approximately 180 degrees from the weld provided approximately the same strain readings.

The yield point for the cylinders has been selected as the deviation from the straight-line portion of the pressure-hoop strain curve, or more appropriately, the proportional limit. This is a valid comparison since the load strain curves for the uniaxial tensile specimens were essentially horizontal after yielding.

Table V. PRESSURE VESSEL STRAIN GAGE DATA

Pressure (psi)	ϵ_{h_1}	ϵ_{a_1}	ϵ_{h_2}	ϵ_{a_2}	ϵ_{h_1}	ϵ_{a_1}	ϵ_{h_2}	ϵ_{a_2}
	μ in/in				μ in/in			
	Cylinder 1A				Cylinder 2A			
0	0	0	0	0	0	0	0	0
250	-	-	-	-	950	335	605	-25
500	1315	300	700	-60	1640	505	1060	-10
750	-	-	-	-	2280	630	1500	25
1000	2665	490	1450	0	2880	745	1920	70
1250	-	-	-	-	3450	845	2320	110
1500	3860	650	2170	90	4025	950	2735	165
1750	4475	730	2555	140	4570	1040	3130	210
2000	5050	805	2935	190	5055	1120	3480	260
2250	5655	870	3375	230	5580	1205	3870	300
2350	-	-	-	-	5845	1240	4050	310
2450	-	-	-	-	6105	1265	4200	325
2500	6350	930	3835	260	-	-	-	-
2550	-	-	-	-	6420	1290	4380	340
2600	6810	950	4070	265	-	-	-	-
0	690	-110	370	-60	790	+55	415	-65
3150	B U R S T				-	-	-	-
3400	-	-	-	-	B U R S T			
	Cylinder 1B				Cylinder 2B			
0	0	0	0	0	0	0	0	0
500	780	455	725	420	1170	270	640	-170
1000	1740	680	1660	660	2180	460	1605	-130
1500	2790	880	2670	875	3140	610	2570	-40
1750	-	-	-	-	3660	710	3150	+20
2000	3790	1050	3645	1060	4100	780	3620	+60
2250	4325	1140	4170	1160	4600	870	4300	110
2350	4550	1180	4385	1205	-	-	-	-
2450	4820	1220	4650	1255	-	-	-	-
2500	-	-	-	-	5100	950	5100	150
2550	5025	1230	4845	1270	-	-	-	-
2600	BURST AT DEFECT				5370	975	5570	170
2650	5320	1215	5120	1270	-	-	-	-
2700	-	-	-	-	5675	995	6110	175
2750	5690	1150	5440	1250	-	-	-	-
2800	-	-	-	-	COULD NOT BALANCE			
0	340	-120	240	-70	530	5	740	-140
3450	-	-	-	-	B U R S T			

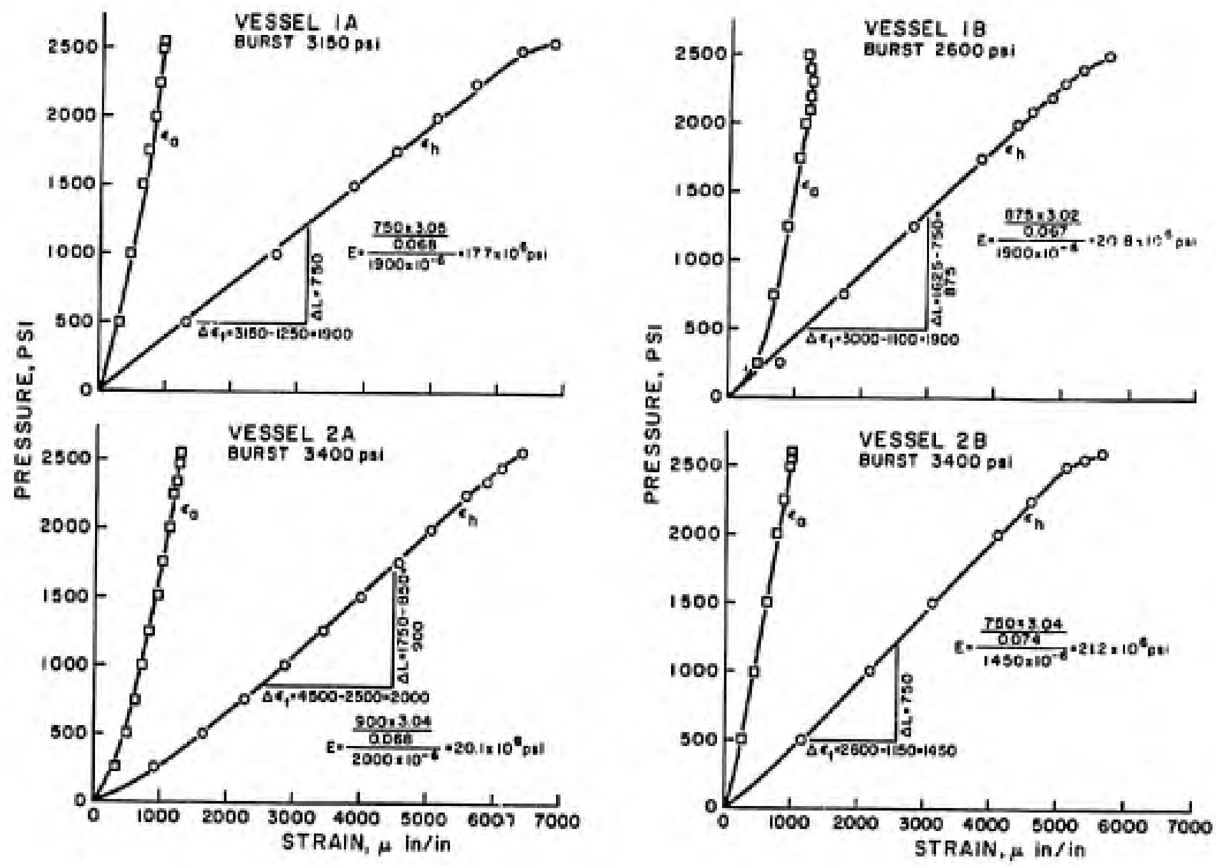


Figure 6. AXIAL AND HOOP STRAIN VALUES

The Hooke's law relationships for both the isotropic and anisotropic material are presented in Appendixes A and B. Using these equations with the measured strain values, the results listed in Table VI are obtained.

The two sets of equations used to calculate the principal stresses in the vessel at yield resulted in approximately the same values. This resulted because the sheet had essentially the same elastic constants in the two directions tested.

The predicted yield strength improvements may be calculated by solving Equation 2 and setting the stress ratio equal to a constant ($K = \sigma_h/\sigma_a$). The following equation is obtained:

$$\frac{\sigma_h}{x_o} = \sqrt{\frac{(1+R_T)\ R_L\ K^2}{(1+R_T)\ R_L K^2 + (R_L+1)\ R_T - 2R_L R_T K}}. \qquad (5)$$

Calculating the anisotropic stress ratios from Table VI, and using Equation 5, the measured and calculated strength ratios are presented in Table VII.

Table VI. CALCULATED YIELD STRESSES ON TEST CYLINDERS

Yield Pressure (psi)	Cylinder Number			
	1A	2A	1B	2B
	2500	2500	2550	2700
Isotropic				
σ_h (ksi)	137	136	112	124
σ_a (ksi)	67	75	64	65
Anisotropic				
σ_h (ksi)	142	142	111	123
σ_a (ksi)	66	72	68	67

Table VII. MEASURED AND PREDICTED UNIAXIAL-BIAXIAL YIELD STRENGTH RATIOS

	Vessel Number			
	1A	2A	1B	2B
Measured Stress Ratio $\frac{\sigma_h}{\sigma_a}$	2.15	1.98	1.63	1.83
Measured Hoop Yield Stress to Uniaxial Yield $\frac{\sigma_h}{x_o}$	1.25	1.25	1.00	1.10
Calculated from Equation 5 $\frac{\sigma_h}{x_o}$	1.35	1.39	1.37	1.36

The pressure vessels manufactured from sheet A exhibited measured biaxial yield strength ratios of 1.25 each, and these values are somewhat less than the calculated values. Vessel 1B was pressurized to 2750 psi during the strain recording, and burst prematurely at 2600 psi when the vessel was repressurized to burst. A defect was located on the inside of the pressure vessel. A possible explanation for the yield values, being lower than those predicted by the anisotropic yield theory, is that the residual stresses are not completely relieved by the relatively low annealing temperatures.

The biaxial burst strengths determined, using the thin-wall pressure formula ($\sigma_B = Pr/t$) and the radius and wall thickness near the origin of fracture with the biaxial-to-uniaxial ultimate ratios, are presented in Table VIII.

Extremely high burst-to-ultimate tensile strength ratios were obtained on the cylinders fabricated from sheet A. Lower burst strengths were exhibited by the vessels fabricated from sheet B; however, the values were still considerably higher than would be expected from uniaxial tensile properties. It should be noted that the wall thicknesses at the origin of failures on all vessels were thinner than those where the gages were located.

Table VIII. PRESSURE VESSEL BURST STRENGTHS

Burst Strength	Vessel Number			
	1A	2A	1B	2B
$\sigma_B = \frac{Pr}{t}$ (ksi)	213	200	164	197
$\frac{\sigma_B}{UTS}$ (ksi)	1.81	1.70	1.36	1.63

Photographs of the failed pressure vessels are presented in Figure 7. All pressure vessels failed in a ductile manner diametrically opposite from the longitudinal weld. Since the conclusion of this testing, Douglas Missile and Space Systems Division has published pressure vessel data using the same alloy.[7] The results for both a 1:1 and 2:1 stress ratio exhibited slightly lower than predicted biaxial yield strengths and higher burst strengths than would be expected based upon the measured R values. As indicated in these studies, the R value can vary throughout the sheet and also may change as a function of strain or stress field. However, the data obtained on the A vessels and those obtained by Douglas are in general agreement. The limited data obtained in this study demonstrate that some biaxial yield improvement and significant burst strength improvements are possible from the use of textured sheet material. Considerable additional work is needed to more adequately prove the feasibility of using these types of materials in structures.

CONCLUSIONS

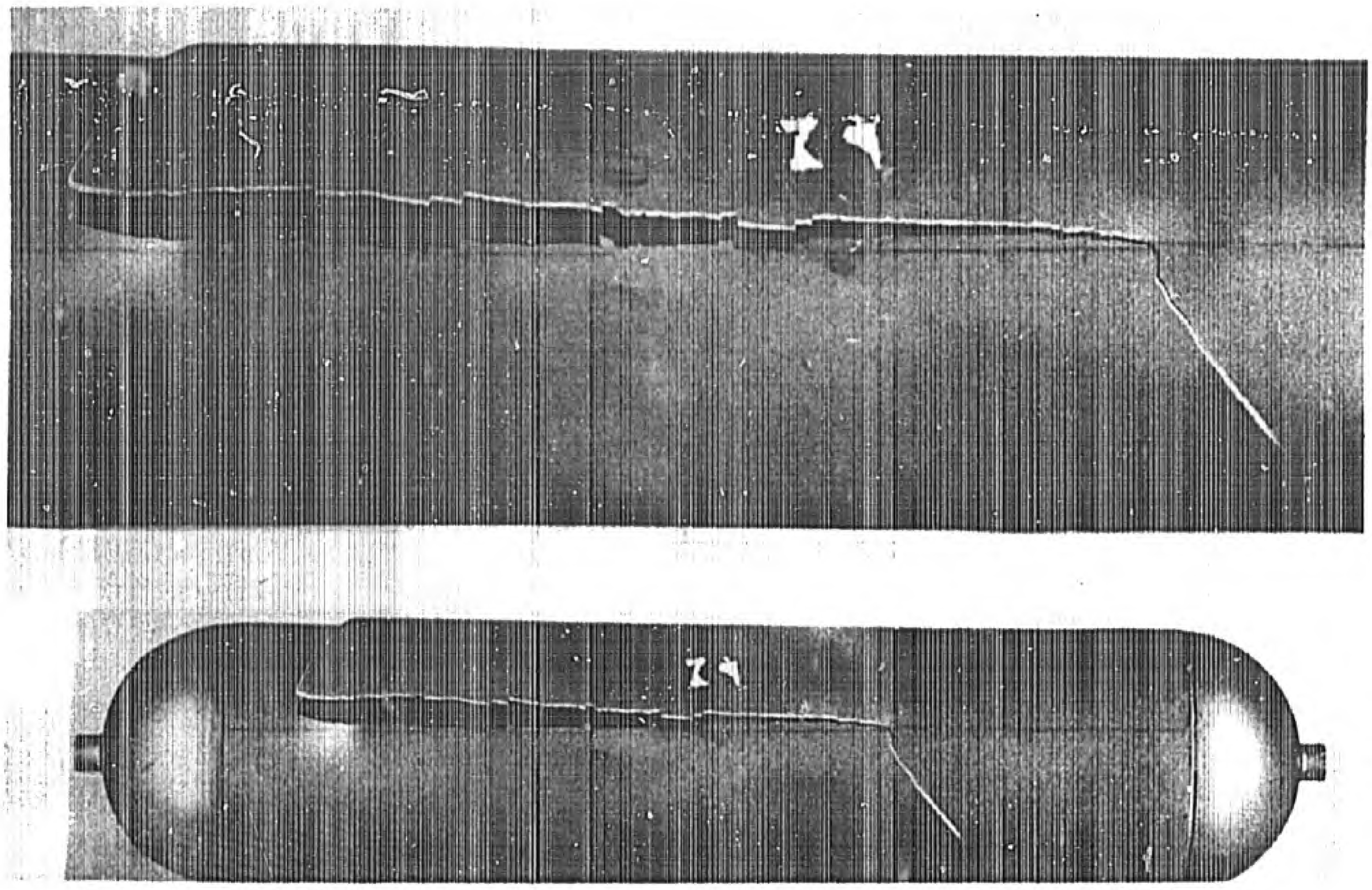
1. Approximately a 25 percent biaxial yield strength improvement over the uniaxial values was obtained for the two pressure vessels fabricated from sheet A, that sheet on which $R_T = R_L$. The two vessels fabricated from sheet B provided lower biaxial yield strength values than would be predicted by the Von Mises yield criteria (15%). The longitudinal plastic strain ratio was lower than the transverse strain ratio ($R_T \neq R_L$) on sheet B.

2. Burst strength/tensile strength ratios were obtained on all pressure vessels. They were significantly higher than would be predicted by extrapolating the Hill-Backofen yield theory to maximum load.

3. General agreement was obtained between the predicted and measured biaxial/uniaxial tensile ratios obtained with the plane strain specimens over a wide annealing temperature range and for several titanium alloys.

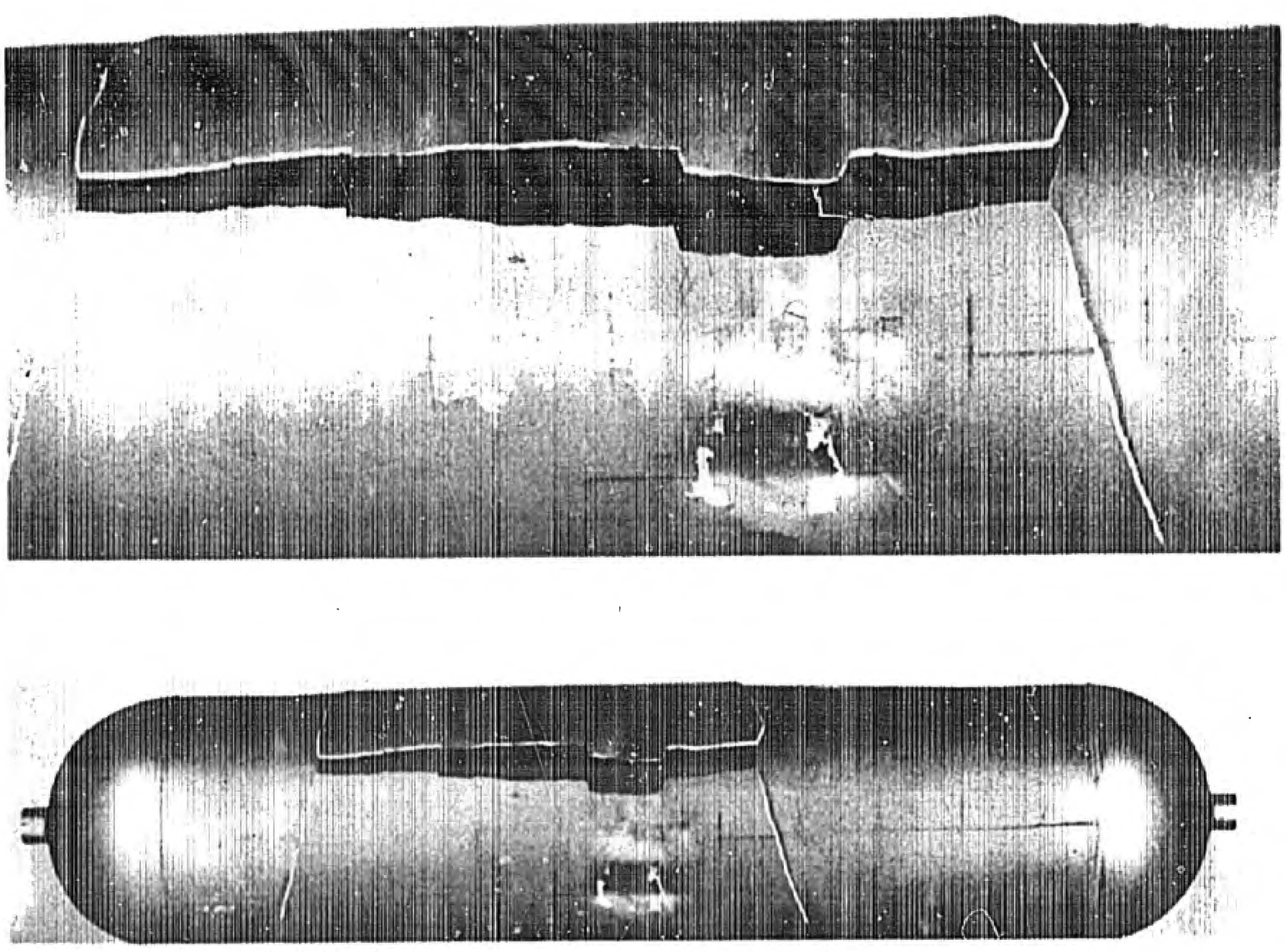
RECOMMENDATIONS

It is recommended that considerable additional development and testing be performed on pressure vessels fabricated from sheet materials with various degrees of texture to prove adequately the feasibility of using these materials and to establish the yield and burst strength relationships. However,



Pressure Vessel 1A - Yield Pressure 2500 PSI; Burst Pressure 3150 PSI.

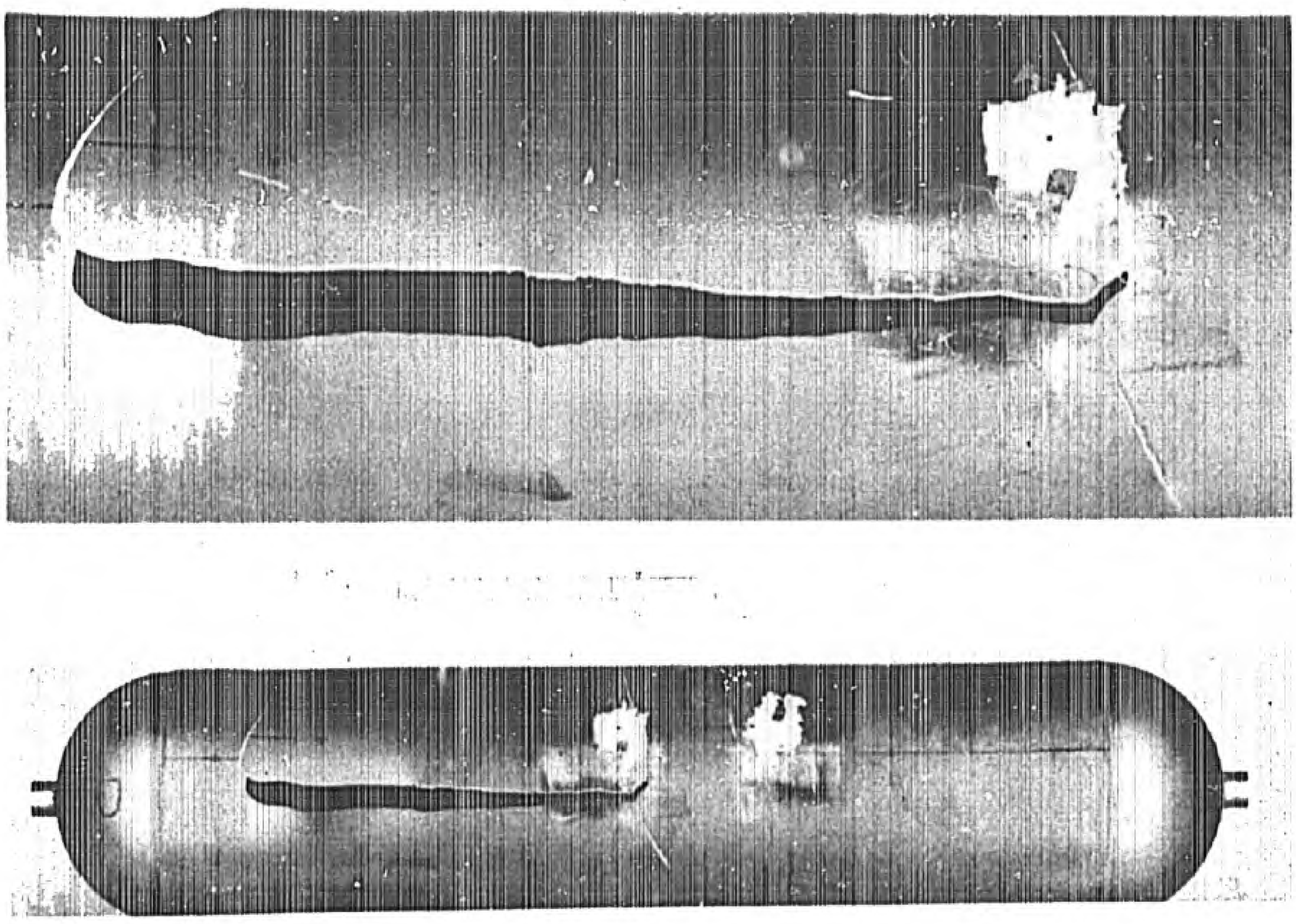
19-066-251/AMC-65



Pressure Vessel 2A - Yield Pressure 2550 PSI; Burst Pressure 3400 PSI.

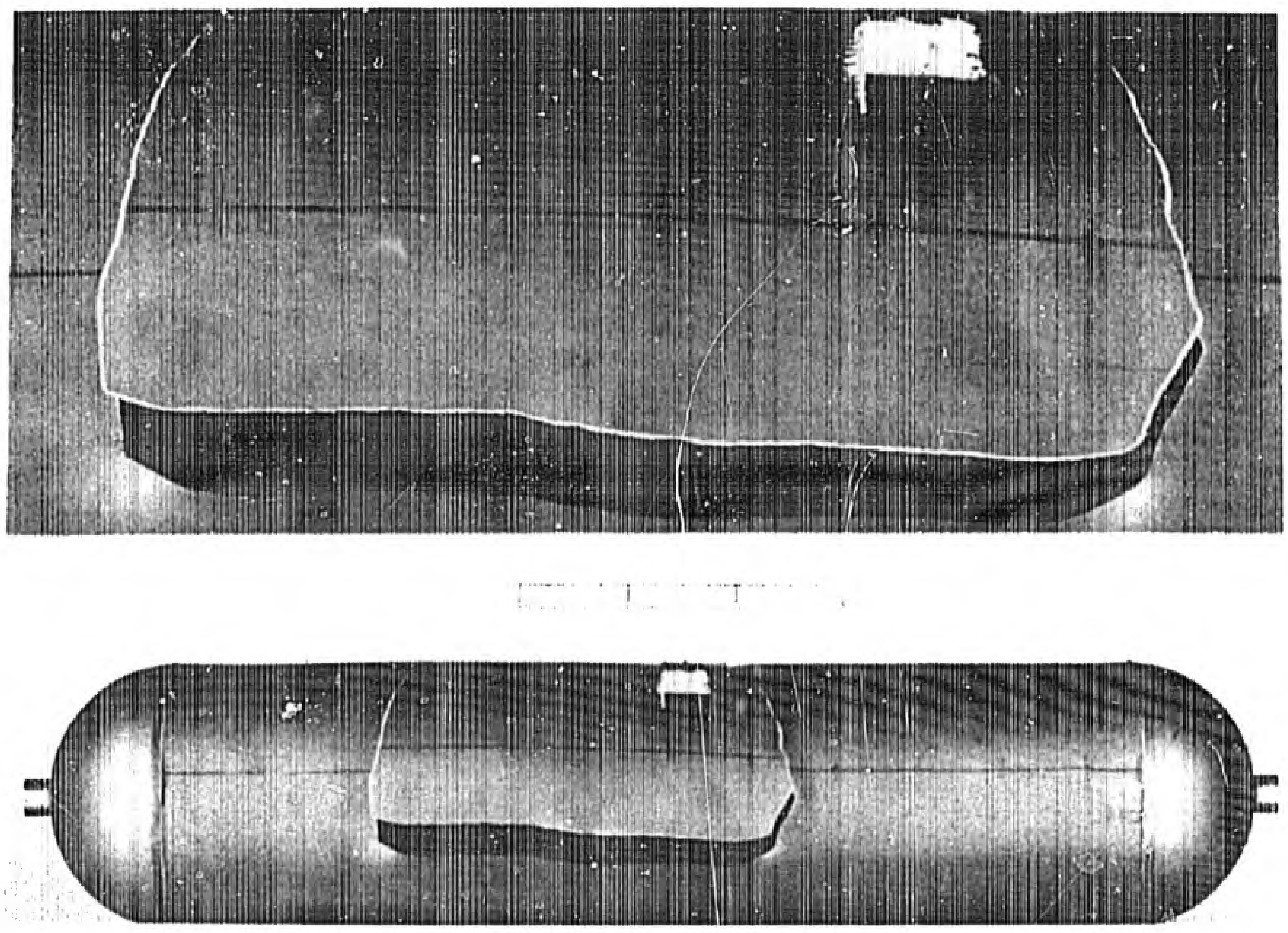
19-066-364/AMC-65

Figure 7a. PRESSURE VESSELS, Ti-5Al-2.5Sn



Pressure Vessel 1B – Yield Pressure 2550 PSI; Burst Pressure 2600 PSI.

19-066-363/AMC-65



Pressure Vessel 2B – Yield Pressure 2600 PSI; Burst Pressure 2400 PSI.

19-066-299/AMC-65

Figure 7b. PRESSURE VESSELS, Ti-5Al-2.5Sn in order to employ these materials, semi-production processing studies are required to produce highly textured sheet alloys which will have a uniform texture over the entire sheet. The desirability of performing these studies on the Ti-6Al-4V alloy, which may be solution treated and aged to the 150 to 160 ksi yield strength level, is evident. A 50 percent increase in the biaxial burst strength on this alloy will result in materials demonstrating strength-to-weight ratios of 1.5 X 10^6 inches. Some of this work is now in progress.

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APPENDIX A

HOOKE'S LAW FOR ISOTROPIC MATERIALS

Considering only principal stresses:

$$\begin{aligned}
\varepsilon_x &= \frac{1}{E}\,[\sigma_x - \mu\,(\sigma_y + \sigma_z)],\\
\varepsilon_y &= \frac{1}{E}\,[\sigma_y - \mu\,(\sigma_x + \sigma_z)], \qquad \text{(A-1)}\\
\varepsilon_z &= \frac{1}{E}\,[\sigma_z - \mu\,(\sigma_y + \sigma_x)].
\end{aligned}$$

For the case of a thin-walled cylindrical pressure vessel, the thickness stress is zero ($\sigma_t = 0$), and considering only the surface strains where h = hoop direction and a = axial directions:

$$\begin{aligned}
\varepsilon_h &= \frac{1}{E}\,[\sigma_h - \mu\sigma_a] \\
& \qquad\qquad\qquad \text{(A-2)}\\
\varepsilon_a &= \frac{1}{E}\,[\sigma_a - \mu\sigma_h].
\end{aligned}$$

Solving equations A-2 simultaneously for σ_a and σ_h:

$$\begin{aligned}
\sigma_h &= \frac{E}{1-\mu^2}\,[\varepsilon_h + \mu\varepsilon_a],\\
& \qquad\qquad\qquad \text{(A-3)}\\
\sigma_a &= \frac{E}{1-\mu^2}\,[\varepsilon_a + \mu\varepsilon_h].
\end{aligned}$$

APPENDIX B

HOOKE'S LAW FOR ANISOTROPIC MATERIAL

Considering only principal stresses

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \mu_y \frac{\sigma_y}{E_y} - \frac{\mu_z \sigma_z}{E_z},$$
$$\varepsilon_y = \frac{\sigma_y}{E_y} - \mu_x \frac{\sigma_x}{E_x} - \frac{\mu_z \sigma_z}{E_z}, \qquad \text{(B-1)}$$
$$\varepsilon_z = \frac{\sigma_z}{E_z} - \mu_x \frac{\sigma_x}{E_x} - \frac{\mu_y \sigma_y}{E_y}.$$

For the case of a thin-walled cylindrical pressure vessel, the thickness stress is zero ($\sigma_t = 0$), and considering only the surface strains where h = hoop direction and a = axial direction:

$$\varepsilon_h = \frac{\sigma_h}{E_h} - \mu_a \frac{\sigma_a}{E_a}$$
$$\varepsilon_a = \frac{\sigma_a}{E_a} - \mu_h \frac{\sigma_h}{E_h}. \qquad \text{(B-2)}$$

Solving equations B-2 simultaneously for σ_h and σ_a:

$$\sigma_h = \frac{E_h\,[\varepsilon_h + \mu_a\,\varepsilon_a]}{(1 - \mu_a\,\mu_h)},$$
$$\sigma_a = \frac{E_a\,[\varepsilon_a - \mu_h\,\varepsilon_h]}{(1 - \mu_a\,\mu_h)}. \qquad \text{(B-3)}$$

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