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BORON/ALUMINUM-GRAPHITE/RESIN ADVANCED FIBER COMPOSITE HYBRIDS

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BORON/ALUMINUM-GRAPHITE/RESIN ADVANCED FIBER COMPOSITE HYBRIDS

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Abstract

An investigation was conducted to determine the fabrication feasibility and to assess the potential of adhesively-bonded metal and resin matrix fiber composite hybrids as an advanced material, for aerospace and other structural applications. The results of fabrication studies and of evaluation of physical and mechanical properties show that using this hybrid concept it is possible to design a composite which, when compared to nonhybrid composites, has improved transverse strength, transverse stiffness, and impact resistance with only a small penalty on density and longitudinal properties. The results also show that laminate theory is suitable for predicting the structural response of such hybrids. The sequence of fracture modes indicates that these types of hybrids can be readily designed to meet fail-safe requirements.

1. INTRODUCTION

Advanced fiber/resin and fiber/metal matrix composites are used most efficiently when the fiber and load directions are coincident. To provide strength or stiffness in more than one direction, composites with fibers oriented in several directions are necessary. Orienting fibers in more than one direction in the same composite, however, reduces their efficiency and can introduce lamination residual stresses comparable to the transverse and shear strength properties of the unidirectional composite. These lamination residual stresses may limit the resistance to mechanical loads of composite components. In particular, it may reduce their resistance to thermal and/or mechanical cyclic load. In addition, commercially available graphite-fiber/resin- and boron-fiber/aluminum composites are inherently weak in impact and erosion resistance.

The aforementioned difficulties may be overcome to a significant extent by the adhesively-bonded metal and resin matrix fiber composite hybrid concept. This can be accomplished by using the best characteristics of resin matrix, metal matrix, and foil materials combined in a hybrid composite. Metal and resin matrix fiber composite hybrids discussed in this paper are adhesively-bonded unidirectional composites made from graphite-fiber/epoxy and boron-fiber/aluminum and a few strategically located titanium foil layers (see schematic figure 1). The addition of the titanium layers improves the laminate transverse properties and eliminates the need for angleplying.

It is the objective of this paper to describe the adhesively-bonded metal and resin matrix fiber composite hybrid concept and report on some experimental and theoretical results which give an indication of its potential. For this investigation laminates were made using various combinations of the above composite systems. Specimens from these laminates were subjected to tension flexure, thin specimen Izod impact, and notch-sensitivity tests. Laminate analysis was used to calculate the lamination residual stresses throughout the hybrids. The results obtained are compared with those of metals and unidirectional composites and are discussed with respect to impact resistance, notch-sensitivity, transverse strength, and ease of fabrication.

The fabrication process, composite configurations, specimen preparation, test methods, and method of analysis are covered in the paper. Comparisons with other composites are reported. Unique applications of the metal and resin matrix hybrid composites to aerospace structures are identified.

In order to have meaningful qualitative and quantitative comparisons among the test results from the several laminates used in this investigation, the geometry of the test specimens was kept as similar as it was practical to do.

2. DESCRIPTION OF COMPOSITE SYSTEMS

2.1 CONSTITUENT PLIES AND MATERIALS

Five types of laminates were made. The types of laminates, laminate designations, constituent materials, and material suppliers are listed below:

Laminate Type	Laminate Designation	Materials	Source
I	Gr/Ep	Unidirectional type A-S graphite fibers with type 3501/epoxy resin in the form of 3-inch wide prepreg tape	Hercules, Inc.
II	B/Al	Diffusion-bonded unidirectional layers of 5.6 mil diameter boron fibers in a 6061 aluminum alloy matrix	Amercom, Inc.
III	B/Al	Monotape layers of 5.6 mil diameter boron fibers in a 6061 aluminum alloy matrix	Amercom, Inc.
		Plies from the above monotape were adhesively bonded using FM 1000 structural adhesive in film form	American Cyanamid Co.
IV	Ti,B/Al (hybrid)	Titanium foil, (6Al-4V) 0.0015-inch thick as rolled	Teledyne Rodney Metals
		Individual monotape layers of 5.6 mil diameter boron fibers in a 6061 aluminum alloy matrix	Amercom, Inc.
		FM 1000 structural adhesive in film form	American Cyanamid Co.
V	Ti,B/Al,Gr/Ep (hybrid)	Titanium foil, (6Al,4V), 0.0015-inch thick	Teledyne Rodney Metals
		Individual monotape layers of 5.6 mil diameter boron fibers in a 6061 aluminum alloy	Amercom, Inc.
		Type A-S graphite/3501 prepreg	Hercules, Inc.
		FM 1000 structural adhesive in film form	American Cyanamid Co.

Thermal, physical and mechanical properties of the above constituent materials are summarized in table 1.

2.2 LAMINATE FABRICATION

Type I. Twelve unidirectional plies of A-S/3501 graphite prepreg tape were assembled and cured in a metal mold using the standard curing conditions recommended by Hercules, Inc. for this type of epoxy resin system.

Type II. Eight unidirectional plies of B/Al were diffusion bonded by the manufacturer, Amercom, Inc. The diffusion bonding conditions consisted of 4500 psi pressure at a temperature of 950°F for one-half hour.

Type III. Seven unidirectional plies of B/Al were adhesively bonded using FM 1000 structural adhesive. Prior to bonding, each B/Al ply was treated with a 10 percent sodium dichromate solution at room temperature for 5 minutes. Each ply was rinsed in water and methyl alcohol, then dried. During the bonding operation, a pressure of 600 psi, a temperature of 375°F, and a time of one-hour were used to cure the adhesive.

Type IV. Five sheets of titanium foil and six unidirectional plies of B/Al were adhesively bonded using FM 1000 structural adhesive. The foil was laid up so that its primary rolling direction was parallel to the fiber direction. Prior to bonding, the titanium foil plies were degreased and treated with a 5 percent hydrogen fluoride solution for 30 seconds at room temperature. This was followed by a water and methyl alcohol rinse and then drying. The prebonding treatment of the B/Al and the time-pressure-temperature cycle for curing was identical to that used for the Type III laminates.

Type V. Five sheets of titanium foil, two plies of B/Al, and six plies of graphite/epoxy were adhesively bonded. The titanium and B/Al plies received the same treatment prior to bonding as the Type IV laminates. FM 1000 adhesive was used for all of the metal-to-metal and metal-to-graphite interface bonds. The graphite/epoxy plies were bonded using the 3501 matrix resin. The time-pressure-temperature cycle was selected to initially cure the graphite/epoxy plies and then effect bonding at the FM 1000 interfaces. The procedure was as follows: After assembling the various components of the laminate in a metal mold, a thermocouple was placed in contact with the edge of the composite. A Wabash-type laminating press was then preheated to 275°F. The cold mold was placed in the press and 15 psig contact pressure was initiated. When the thermocouple reached 100°F, contact pressure was maintained for 16 minutes. A pressure of 600 psig was then initiated and a temperature of 275°F was maintained for another 14 minutes to complete gelation of the epoxy matrix resin. At the end of this time period, the press temperature was increased to 300°F and pressure was maintained for 30 minutes to advance the cure of the epoxy. At the end of this time period, the press temperature was increased to 350°F and pressure was maintained for 120 minutes to complete the cure of the epoxy and the adhesive. The press heaters were turned off and the laminate was permitted to cool under pressure to room temperature.

Photomicrographs of typical cross sections of the above laminates are shown in figure 2. The materials and various plies in these laminates are also indicated in this figure. The detailed arrangement of the materials, plies and their corresponding thicknesses are given in table 2.

3. DESCRIPTION OF TEST PROGRAM

In this section the specimen preparation, instrumentation, types of tests, and procedures are described.

3.1 SPECIMEN PREPARATION

Unidriectional laminates ranging in thickness from 0.05 to 0.06-inches were cut into 1/2-inch width specimens by using a precision wafer cutting machine equipped with a diamond cutting wheel. A specimen layout plan is shown in figure 3.

To determine the notch sensitivity of the laminates being investigated, through-the-thickness center slots were placed in specimens using electrical discharge machining. All notched specimens were machined this way except for the Type I transverse specimen. This specimen was double edge notched using a .005-inch wide cutting wheel. In all cases the notch root radius was .003-inch or less. A single slot length, .017-inch, was used for tests on laminate Types I, II, and V. Two slot lengths, .010-inch and .017-inch, were used for tests on laminate Types III and IV.

Where required, the specimen ends were reinforced with adhesively bonded aluminum or fiber glass tabs. All the specimens for determining longitudinal smooth tensile properties had their ends reinforced. In addition, all Type I specimens that were subjected to tensile loadings had their ends reinforced.

3.2 SPECIMEN INSTRUMENTATION

The specimens used to determine smooth tensile properties were instrumented with strain gages to measure longitudinal and transverse strain.

3.3 TYPES OF TESTS AND PROCEDURES

Composite density. Samples of each of the five laminate types were evaluated for density by using the ASTM D-792 test method for "Specific Gravity and Density of Plastics by Displacement."

Smooth and Notch Tensile Strengths. The smooth and notch tensile specimens were loaded to failure using a hydraulically actuated universal testing machine. Longitudinal specimens had a test section about 3-inches long, while transverse specimens had a test section about 2-inches long. The notched specimens were loaded to failure and the maximum load noted. Loading was halted at convenient intervals when testing the smooth specimens so that strain gage data could be obtained using a digital strain recorder.

Flexural strengths. Test specimens having a length of 3-inches were tested for flexural strength in an Instron testing machine. A 3-point loading system was used with a span of 2-inches.

Izod impact strengths. Unnotched specimens were subjected to Izod impact strength tests using a TMI Impact Tester equipped with a 2-pound hammer. The velocity of the hammer was 11 feet/second.

4. TEST RESULTS AND DISCUSSION

In this section test results obtained for density, tensile smooth and notched flexural, and Izod impact are summarized and discussed.

4.1 DENSITY

The measured densities of the laminates tested are given in the first column of table 3. Note that the density of laminate V (Ti,B/Al,Gr/E_p) is the same as that of E-Glass/epoxy (.075 lb/in^3).

4.2 SMOOTH TENSILE TESTS

Table 3 summarizes the test data obtained from smooth specimens (specimens without slots). This table includes laminate longitudinal (load applied parallel to fibers) and transverse (load applied normal to fibers) tensile properties. Note in this table that the initial tangent moduli and Poisson's ratios are given. As can be seen in table 3, inclusion of titanium foil layers in the hybrids improves the transverse strength properties relative to the unidirectional material. The longitudinal and transverse fracture strains of the two hybrids are approximately equal.

Comparing the results of the diffusion-bonded and adhesively-bonded B/Al laminates in table 3, it is seen that these laminates have approximately equal properties except for the longitudinal fracture stress. The longitudinal fracture stress of the adhesively-bonded laminate is about 70 percent of that of the diffusion bonded laminate

Stress-strain curves for all of the laminate types are shown in figure 4a for loads parallel to fibers and in figure 4b for loads transverse to the fibers. Note that the stress-strain curves are linear to fracture, or nearly so, for specimens loaded parallel to the fibers (fig. 4a). However, specimens loaded transverse to the fibers exhibit considerable nonlinearity (fig. 4b). Curves of Poisson's strain versus axial strain are shown in figure 5.

One interesting result was the failure mode of the Type V laminate (Ti,B/Al,Gr/Ep) tested in longitudinal tension. The boron/aluminum plies failed when the tensile stress produced strain about equal to the fracture strains of the boron fibers. The Gr/Ep plies remained intact and therefore still capable of carrying mechanical load. The authors believe this failure mode to be very significant because these hybrids can be designed to have inherent fail-safe design characteristics.

4.3 NOTCH TENSILE TESTS

The test data obtained from slotted specimens are summarized in table 4. Two interesting points to be observed from the data in table 4 are the following:

(1) The notch effects are small and about the same for both the longitudinal and transverse directions in the hybrid composites.

(2) Notch strengthening for the transverse tensile specimens was observed in both the diffusion-bonded and adhesively-bonded B/Al laminates. This strengthening may be attributed, in part, to the transverse restraining effects of the fibers at the slot ends.

4.4 FLEXURAL TESTS

The test data obtained from subjecting test specimens to 3-point flexural loading are summarized in table 5. The important points to be observed from the data in table 5 are the following:

(1) The hybrid composites exhibit significant improvement in transverse strength compared to other composites.

(2) The hybrid composites exhibit a decrease in the longitudinal flexural strength compared to other composites.

(3) The hybrid composite flexural longitudinal modulus is slightly less than the B/Al composite and greater than the Gr/Ep composite.

(4) The transverse modulus of the Ti,B/Al, Gr/Ep hybrid composite is about four times greater than that of the Gr/Ep composite.

4.5 IMPACT TESTS

Data obtained by subjecting the thin composite specimens to unnotched Izod impact tests are summarized in table 6. Note in table 6 the impact strengths of some other composites and materials are given for comparison purposes. In order to make the comparison meaningful, the Izod impact data were normalized with respect to the cross sectional area of the composite. In table 6, the low and high Izod impact strengths and the number of specimens for each composite or material are given.

The important point to be observed from the data in table 6 is the following:

Using the metal and resin matrix hybrid composite concept, composite materials may be designed with Izod impact resistance approaching that of aluminum. In addition, when the Izod impact values are normalized with respect to density the longitudinal impact resistance of the Type V hybrid is about 70 percent of that of the titanium.

5.0 DESCRIPTION OF THEORETICAL PROGRAM

In this section the calculation method used and results obtained for laminate density, elastic properties, plate-type stiffnesses and lamination residual stress are described.

5.1 DENSITY AND ELASTIC PROPERTIES

Laminate analysis was used to assess the applicability of linear laminate analysis to hybrid composites. For this purpose, the laminate analysis available in the Multilayer Fiber Composite Analysis Computer Code (ref. 1) was used. The inputs for the analysis of the metal and resin matrix hybrid composites consisted of the ply constituent properties data . ble 1 and the ply arrangement and thicknesses data in table 2.

The output of the computer code consists of the following:

(1) composite density
(2) longitudinal, transverse and shear moduli
(3) major and minor Poisson's ratios
(4) plate-type bending stiffnesses, a measure of the structural response of the laminate

The flexural longitudinal and transverse moduli are obtained from the plate-type bending stiffnesses using the following equations:

$$E_{FL} = 12(D_{11}-D_{12}^2/D_{22})/t^3 \qquad (1)$$

$$E_{FT} = 12(D_{22}-D_{12}^2/D_{11})/t^3 \qquad (2)$$

where E denotes modulus; the subscript F flexural, L longitudinal and T transverse; the D's denote plate-type bending stiffnesses with the subscript 1 taken along the fiber direction and 2 transverse to it; and t denotes the laminate thickness.

The results of the laminate analysis via the computer code are summarized in table 7. In this table the flexural moduli predicted by equations (1) and (2) are given. Also, corresponding values for aluminum and titanium are included for comparison purposes. As can be seen from these data, unidirectional hybrid composites can be designed with torsional stiffness equal to that of aluminum.

It is noted that no attempt was made to predict fracture stresses (strains) of the hybrids in the present investigation. However, if the fracture strains in both longitudinal and transverse directions are approximately the same and about equal to the yield strain of the titanium or fracture strain of the boron fibers, table 3, then prediction of hybrid fracture strain should be rather straightforward. Additional experimental data are needed to place the above observation on a firmer basis.

It is also noted that no attampt was made to determine stress intensity factors of the notched composites and hybrids. Since the hybrid composites exhibited small notch-sensitivity, the stress intensity factor for such hybrids might not even be needed.

5.2 LAMINATION RESIDUAL STRESSES

Lamination residual stresses are induced in the constituent material layers of the metal and resin matrix composites because of:

(1) mismatch of the thermal coefficient of expansions
(2) the temperature difference between the cure and room temperatures.

The lamination residual stresses were computed using laminate analysis as is described in reference 2. The results are summarized in table 8.

Comparing lamination residual stresses from table 8 with corresponding fracture (yield) stresses in table 1, it is seen that the lamination residual stresses are relatively low. For example, those in the adhesive are less than 50 percent of the corresponding fracture stresses. Since the adhesive has relatively low stiffness compared to the other constituents, the hybrid can be subjected to considerable mechanical load before the adhesive will reach its fracture stress.

It is noted that the thermal fatigue resistance of the metal and resin matrix hybrid composites needs to be determined.

6. COMPARISONS OF PREDICTED AND MEASURED DATA

Comparing corresponding values from tables 3 and 7, it is seen that the laminate theory predicts densities moduli and Poisson's ratios which are in good agreement with initial measured data. No measured data were obtained for shear modulus, nor measured directly for the plate-type bending stiffnesses.

Comparing corresponding values from table 5 and 7, it is seen that linear laminate theory predicts flexural longitudinal moduli which are in very good agreement with measured data. The comparisons for flexural transverse moduli is fair with the predicted values higher than the measured. This is to be expected since transverse flexural loading strains the specimen nonlinearly as shown in figure 4b.

The important point from the above comparisons is that laminate theory appears to be suitable for predicting the structural response of the metal matrix and resin matrix fiber composite hybrids. And from what has been discussed previously, laminate theory is expected to be applicable for predicting the strength of these hybrids based on constituent plies and materials fracture data.

7. SOME IMPORTANT OBSERVATIONS

The following important observations are worthy of note:

(1) The mechanical test results show that adhesive bonding is a feasible method for producing high quality composites and composites with improved impact and transverse properties.

(2) Using composites in the unidirectional configuration simplifies the fabrication process. Introduction of the titanium layers improves transverse properties sufficiently so that angleplying is not necessary.

(3) The hybrids with the titanium layers will offer distinct advantages over other composites where erosion and impact resistance control the design. In addition these hybrids should be suitable for joints and load transfer in highly loaded components.

(4) Optimum combinations of metal/matrix composites and titanium layers with resin/matrix composites may be possible to meet a multitude of design requirements while maintaining fabrication simplicity and low lamination residual stresses.

(5) The fracture path/surface of the hybrids tested in this investigation appeared to be well defined as compared with advanced nonhybrid composites. Photographs of fractured specimens are shown in figure 6.

8. CONCLUSIONS

The results of an investigation to determine the feasibility of fabricating and to evaluate the physical and mechanical properties of adhesively-bonded metal matrix and resin matrix fiber composite hybrids lead to the following conclusions:

(1) High quality hybrid composites can be fabricated by adhesive bonding.

(2) Mechanical tests of adhesively-bonded composite hybrids showed that it is possible to make a composite with the following desirable properties:

(a) Longitudinal strength and stiffness approaching corresponding properties of other advanced fiber composites.

(b) Transverse flexural strength approaching that of the yield strength of titanium, 6Al-4V alloy.

(c) Longitudinal impact resistance approaching that of aluminum.

(d) Transverse and shear stiffnesses comparable to those of 6061 aluminum.

(e) Density comparable to that of commercially-available E-glass/epoxy composites.

(3) Judicious location of the titanium-foil layers in the laminates may result in predictable high energy absorption failure modes for these hybrids. Along the fiber direction fracture is governed by the fiber fracture strain. Transverse to the fiber direction and in shear, fracture appeared to be governed by the yield strain of the titanium foils.

(4) The lamination residual stresses in the adhesive are about 50 percent of its corresponding failure stresses, therefore, capacity remains for carrying mechanical load in the hybrid composites.

(5) The Ti,B/Al,Gr/Ep hybrid exhibited a primary fracture whereby the (B/Al) plies failed leaving the Gr/Ep plies intact. This failure sequence might be used to design fail-safe structural components.

9. REFERENCES

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Mr. Lark is assigned to the Structures Section, Composites and Structures Branch of the NASA-Lewis Research Center, Cleveland, Ohio where he has been since 1958. He received his B.S. in Chemical Engineering (1948) from Case Institute of Technology. His current work assignment involves the project management of in-house and contractual programs for the development of composite pressure vessels and composite materials for aircraft engine components. Other experience includes the development of positive expulsion devices, advanced fibers, resins and adhesives. He has contributed significantly to the advancement in the state-of-the-art of composite pressure vessel and positive expulsion technology and advanced composites in general. He is currently a member of ASTM and the MIL-HDBK 17 Committee.

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Timothy L. Sullivan is with the Structures Section where he has been since 1964. He received his B.S. in Aeronautical Engineering (1959) from the University of Detroit, M.S. (1960) and engineer's degree (1961) in Aeronautics from the California Institute of Technology. He is presently involved in mechanical property characterization of and mechanical test development for advanced composite materials. Prior to 1971 he was involved in studies of the fracture mechanics of high strength sheet materials in cryogenic environments. He is a member of Sigma Xi.

TABLE I. - PROPERTIES OF CONSTITUENTS USED TO MAKE HYBRID

COMPOSITES (FROM MATERIAL SUPPLIERS).

Property	Units	Ti (6 Al-4V)	Adhesive (FM-1000)	B/Al (5.6/6061)	Gr/Ep (A-S/3501)
Density	lb/in^3	.16	.042	.095	.057
Nominal thickness	in.	.0015	.0005	.0070	.0050
Approximate fiber volume	percent	----	---	50	60
Modulus	10^6 psi				
E_1		16.0	.20	33.8	18.5
E_2		16.0	.20	21.0	2.0
G_{12}		6.2	.07	7.2	.61
G_{23}		6.2	.07	6.8	.37
Poisson's ratio					
ν_{12}		.30	.40	.25	.25
ν_{23}		.30	.40	.39	.47
Coefficient of thermal expansion	10^{-6} in./in./°F				
α_1		5.8	40.0	3.3	.33
α_2		5.8	40.0	10.7	16.2
Fracture stress	10^3 psi				
S_{1T}		120(1)	6(2)	220	181
S_{1C}		120(1)	10(2)	250	165
S_{2T}		120(1)	6(2)	20	8
S_{2C}		120(1)	10(2)	[illegible]	25
S_S		70	7	23	13

(1) 0.2% offset yield strength
(2) Estimated value
Subscript notation: 1, along fiber direction
2, transverse to fiber
3, through thickness
T, tension
C, compression
S, shear

TABLE II. - LAMINATE DESCRIPTIONS

Laminate														
Composition			Composition			Composition			Composition			Composition		
(Gr/Ep)			Dif. Bonded (B/Al)			Adh. Bonded (B/Al)			Ti/(B/Al)			Ti/(B/Al)/(A-S/E)		
Type-I			Type-II			Type-III			Type-IV			Type-V		
Layer no.	Material	t,(1) in.	Layer no.	Material	t, in.	Layer no.	Material	t, in.	Layer no.	Material	t, in.	Layer no.	Material	t, in.
1	A-S/3501	0.0049	1	B/Al (5.6 mil, 6061)	0.0069	1	B/Al	0.0074	1	Ti (6-4)	0.0015	1	Ti	0.0015
2			2			2	FM 1000	.0003	2	FM 1000	.0001	2	FM 1000	.0007
3			3			3	B/Al	.0074	3	Ti	.0015	3	Ti	.0015
4			4			4	FM 1000	.0003	4	FM 1000	.0001	4	FM 1000	.0007
5			5			5	B/Al	.0074	5	B/Al	.0074	5	B/Al	.0074
6			6			6	FM 1000	.0003	6	FM 1000	.0001	6	FM 1000	.0007
7			7			7	B/Al	.0074	7	B/Al	.0074	7	A-S/E	.0050
8			8			8	FM 1000	.0003	8	FM 1000	.0001	8	A-S/E	.0050
			(Total thickness 0.0552)											
9						9	B/Al	.0074	9	B/Al	.0074	9	A-S/E	.0050
10						10	FM 1000	.0003	10	FM 1000	.0001	10	FM 1000	.0007
11						11	B/Al	.0074	11	Ti	.0015	11	Ti	.0015
12						12	FM 1000	.0003	12	FM 1000	.0001	12	FM 1000	.0007
(Total thickness 0.0588)														
						13	B/Al	.0074	13	B/Al	.0074	13	A-S/E	.0050
						(Total thickness 0.0536)								
									14	FM 1000	.0001	14	A-S/E	.0050
									15	B/Al	.0074	15	A-S/E	.0050
									16	FM 1000	.0001	16	FM 1000	.0007
									17	B/Al	.0074	17	B/Al	.0074
									18	FM 1000	.0001	18	FM 1000	.0007
									19	Ti	.0015	19	Ti	.0015
									20	FM 1000	.0001	20	FM 1000	.0007
									21	Ti	.0015	21	Ti	.0015
									(Total thickness 0.0529)			(Total thickness 0.0579)		

(1)t Denotes layer thickness.

TABLE III. - PROPERTIES OF SMOOTH TENSILE SPECIMENS

Laminate type	Constituents	Density, lb/in³	Fracture strength, 10³ psi		Fracture strain, percent		Initial modulus of elasticity, 10⁶ psi		Initial Poisson's ratio	
			Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
I	Gr/Ep	0.057	164	5.6	1.02	0.34	15	1.8	0.33	0.03
II	B/Al(1)	.089	228	17.7	.79	.12	32	25	.24	.14
III	B/Al(2)	.091	159	23.7	.67	.21	30	23	.26	.14
IV	Ti, B/Al	.098	160	44.1	.68	.88	27	20	.27	.18
V	Ti, B/Al, Gr/Ep	.074	125	31.5	.73	1.01	18	8.5	.25	.11

(1)Diffusion-bonded

(2)Adhesive-bonded

TABLE IV. - PROPERTIES OF NOTCHED TENSILE SPECIMENS

Laminate type	Constituents	Notch length, in.	Net fracture strength 10^3 psi		Notch strength ÷ Unnotched strength	
			Long.	Trans.	Long.	Trans.
I	Gr/Ep	0.17	(3)	[illegible](4)	1.00	.[illegible]9(4)
II	B/Al(1)	.17	157	27.5	.69	1.5[illegible]
III	B/Al(2)	.10	14[illegible]	[illegible]7.9	.89	1.18
III	B/Al(2)	.17	140	22.4	.88	.9[illegible]
IV	Ti, B/Al	.10	140	39.0	.87	.88
IV	Ti, B/Al	.17	134	36.[illegible]	.84	.83
V	Ti, B/Al, Gr/Ep	.17	98	24.0	.76	.7[illegible]

(1) Diffusion-bonded
(2) Adhesive-bonded
(3) No notch growth, specimen split parallel to fibers
(4) Double edge notch specimen

TABLE V. - PROPERTIES OF FLEXURAL SPECIMENS

Laminate type	Constituents	Fracture stress 10^3 psi		Modulus(1) 10^6 psi	
		Long.	Trans.	Long.	Trans.
I	Gr/Ep	246	8	20	2.5
II	B/Al(2)	304	39	49	14
III	B/Al(3)	204	46	31	17
IV	Ti, B/Al	204	97	27	17
V	Ti, B/Al, Gr/Ep	185	85	22	11

(1) The modulus was computed using chart deflection and a calibration factor to account for instron compliance. These values are only approximate.
(2) Diffusion-bonded
(3) Adhesive-bonded

TABLE VI. - SUMMARY OF THIN-SPECIMEN IZOD IMPACT STRENGTH RESULTS AND COMPARISONS WITH SOME OTHER MATERIALS. (SPECIMEN NOMINAL DIMENSIONS: 0.50 INCHES WIDE BY 0.06 INCHES THICK).

Laminate type	tuents	Test direction	IZOD impact strength in.-lb/in.^{2}		Number of specimens
			Low	High	
I	Gr/Ep	Long.	325	357	
		Trans.	44	48	2
II	B/Al(1)	Long.	277	286	2
		Trans.	229	247	2
III	B/Al(2)	Long.	155	216	2
		Trans.	98	159	4
IV	Ti, B/Al	Long.	247	253	2
		Trans.	179	224	4
V	Ti, B/Al, Gr/Ep	Long.	634	720	2
		Trans.	186	202	2

Other Materials

HT-S/PMR-PI(3)	Long.	204	206	2
	Trans.	40	43	2
Glass-fabric/epoxy	---	249	255	3
4-mil diam B/6064-Al	Long.	253	272	2
Aluminum 0.6061	---	756	914	2
Titanium (6Al-4v)	---	2525	2558	2

(1) Diffusion-bonded
(2) Adhesive-bonded
(3) PMR-polymerization of monomeric reactants; PI-polyimide

TABLE VII. - SUMMARY OF PREDICTED[1] LINEAR ELASTIC CONSTANTS AND PLATE-TYPE BENDING STIFFNESS FOR HYBRID COMPOSITES AND COMPARISON WITH SOME MEASURED METAL VALUES

Laminate type	Constituents	Density lb/in.^{3}	Modulus 10^6 psi			Poisson's ratio		Plate type bending stiffness[2] lb-in.				Flexural modulus 10^6 psi	
			Long.	Trans.	Shear	Major	Minor	D_{11}	D_{12}	D_{22}	D_{33}	Long.	Trans.
I	Gr/Ep	0.057	18.5	2.0	0.61	0.35	0.027	51[illegible]	8.5	54.1	10.3	18.5	2.0
II	B/Al[3]	.095	33.0	21.0	7.20	.25	.16	482	77.6	306	101	33.0	21.0
III	B/Al[4]	.093	31.9	20.3	6.90	.25	.16	430	68.5	274	90.1	31.9	20.3
IV	Ti, B/Al	.103	30.0	19.9	6.92	.26	.17	353	65.0	247	82.8	27.2	19.0
V	Ti, B/Al, Gr/Ep	.07[illegible]	20.2	8.7	3.0	.26	.11	359	60.5	226	75.9	21.1	13.3
Metal (Measured values)													
Al (6061)		.098	10.0	10.0	3.61	.33	.33	203	65.5	203	130	10.0	10.0
Ti (6Al-4V)		.160	16.0	16.0	6.2	.30	.30	316	95.0	316	223	16.0	16.0

(1) Properties predicted via Multilayer Fiber Composite Computer Code (ref. 1)

(2) Plate-type stiffness for metals were computed from the relation $D_{11} = D_{22} = Et^3/12(1-\nu^2)$ and $D_{33} = Et^3/6$ where t was taken as 0.06 in.

(3) Diffusion-bonded

(4) Adhesive-bonded

TABLE VIII. - COMPUTED LAMINATION RESIDUAL STRESSES IN COMPOSITES DUE TO COOLING FROM 350° F PROCESSING TEMPERATURE

Laminate	Constituents	Residual stress, 10^3 psi							
		Ti foil		B/Al		Gr/Ep		Adhesive	
		Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
I	Gr/Ep	---	---	---	---	0	0	---	---
II	B/Al[1]	---	---	0	0	---	---	---	---
III	B/Al[2]	---	---	-0.1	-0.1	---	---	3.6	3.1
IV	Ti, B/Al	5.6	-19.3	-1.0	3.2	---	---	3.6	3.1
V	Ti, B/Al, Gr/Ep	12.1	-19.6	11.7	2.4	-9.5	3.1	3.6	3.2

(1) Diffusion-bonded

(2) Adhesive-bonded

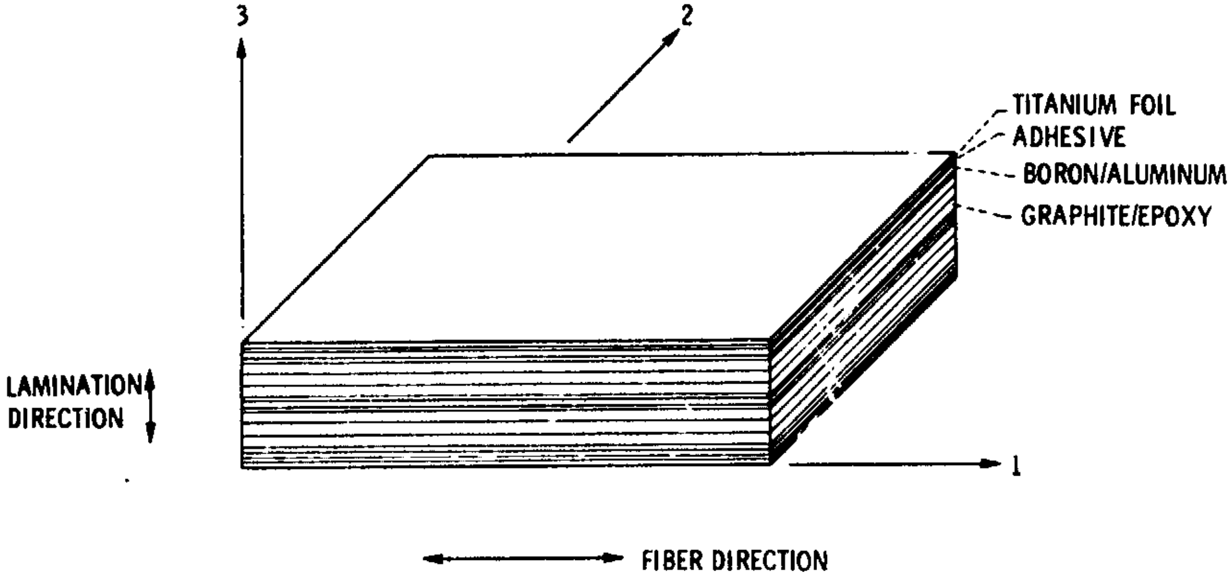

Figure 1. - Schematic of adhesively-bonded metal matrix and resin matrix fiber composite hybrid.

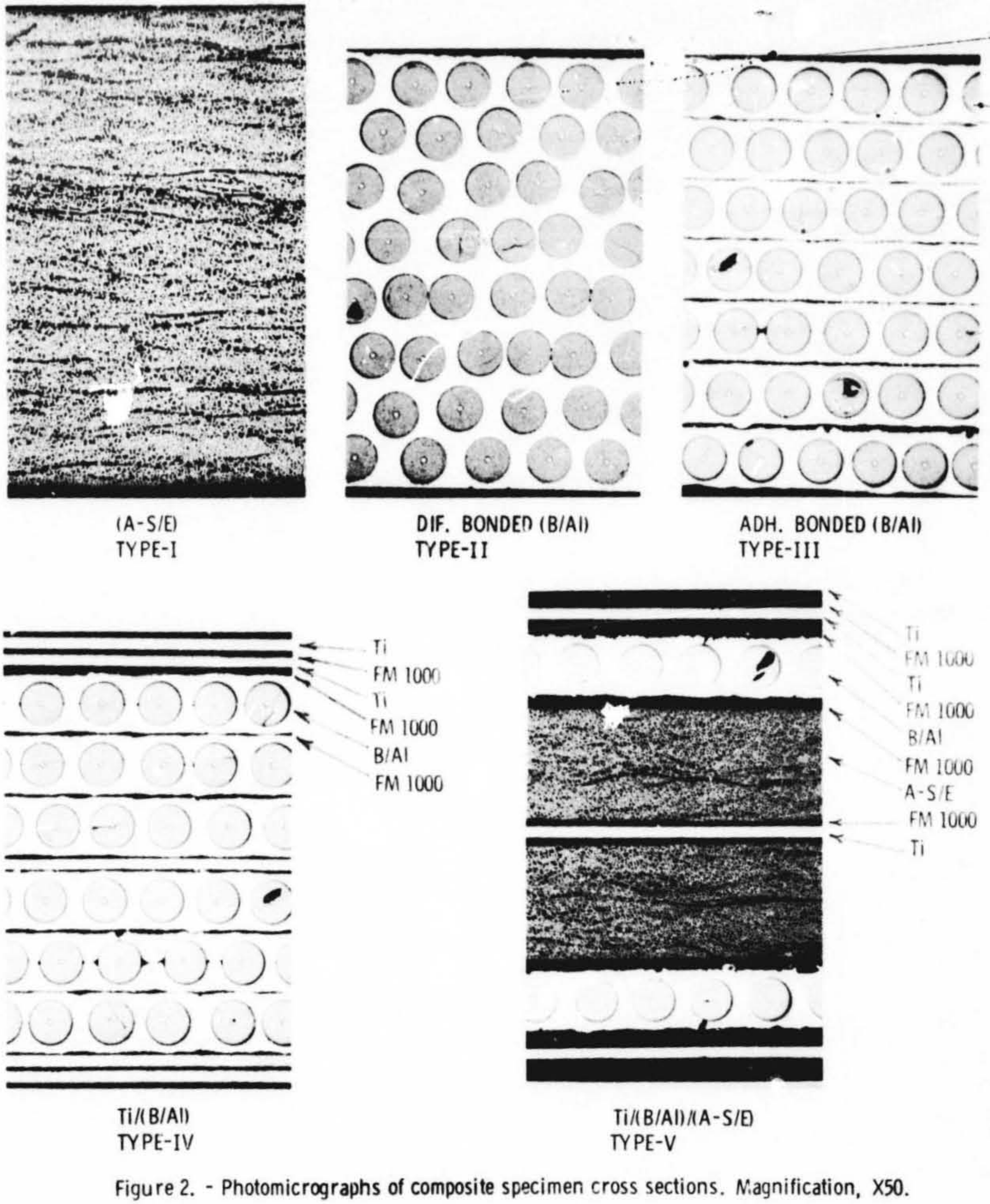

Figure 2. - Photomicrographs of composite specimen cross sections. Magnification, X50.

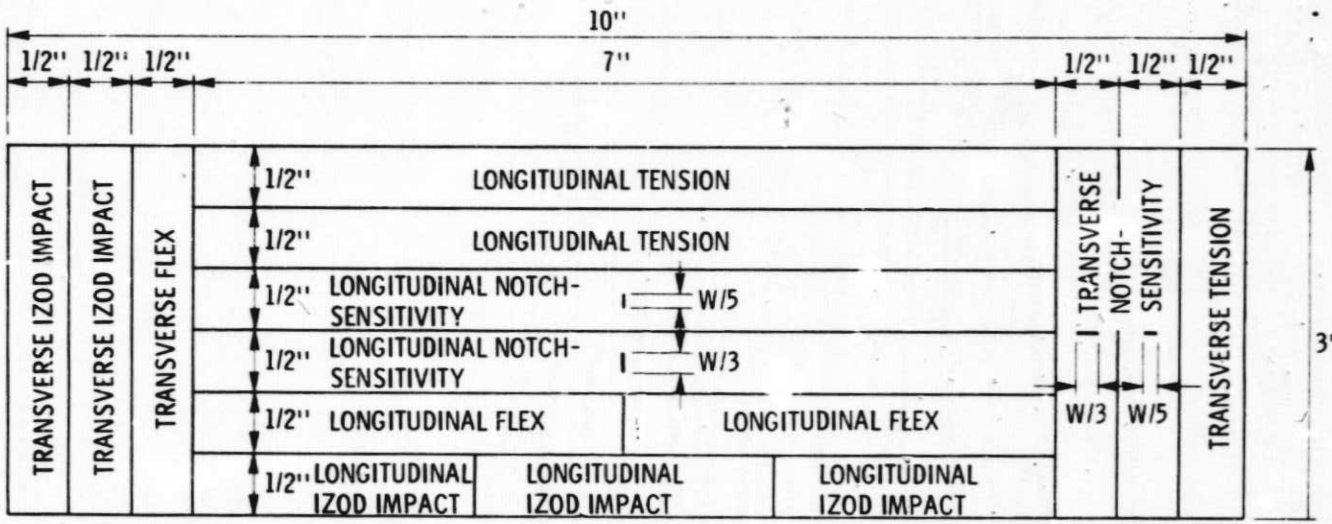

Figure 3. - Typical specimen layout plan. (Nominal dimensions.)

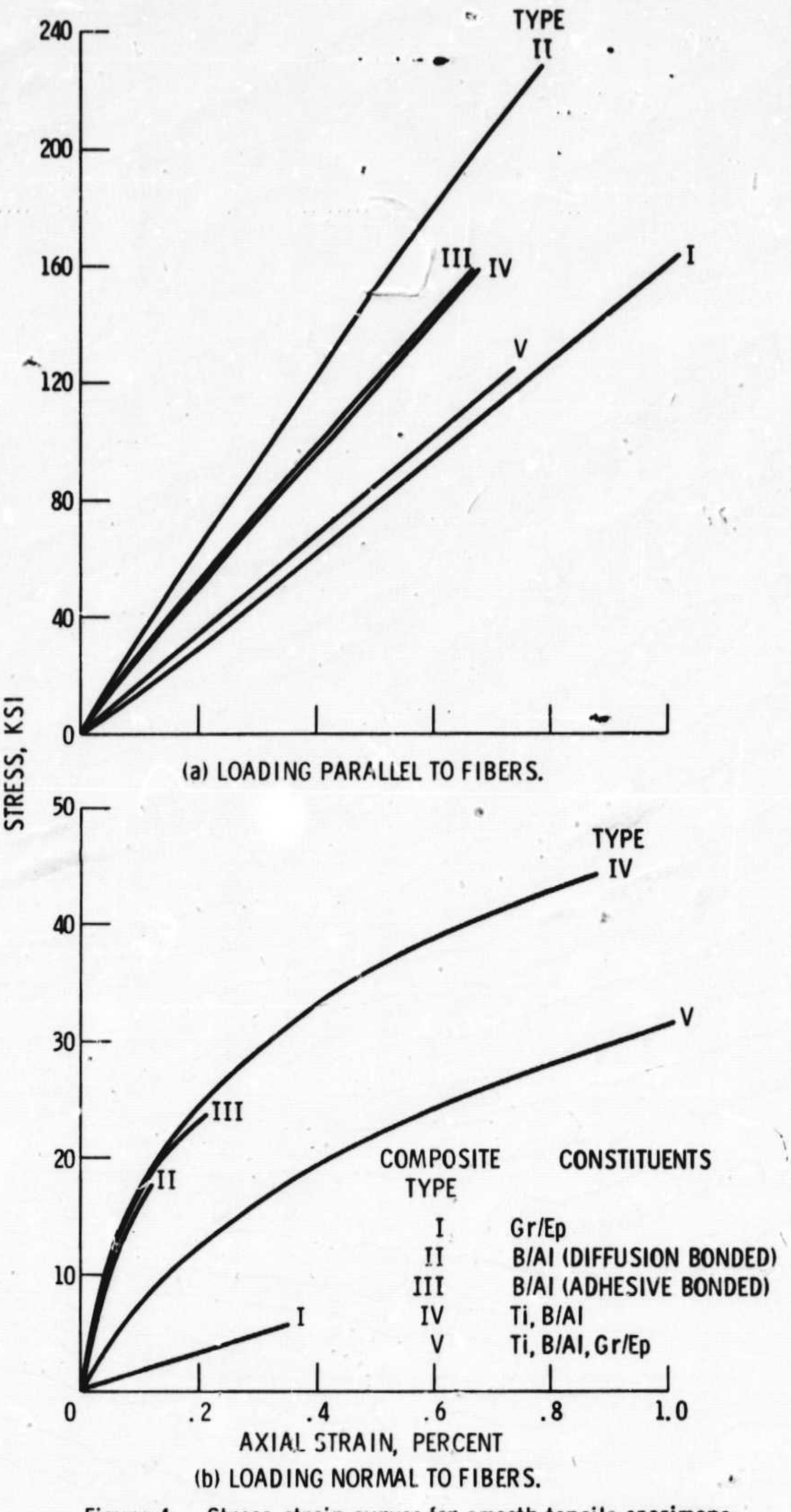

Figure 4. - Stress-strain curves for smooth tensile specimens.

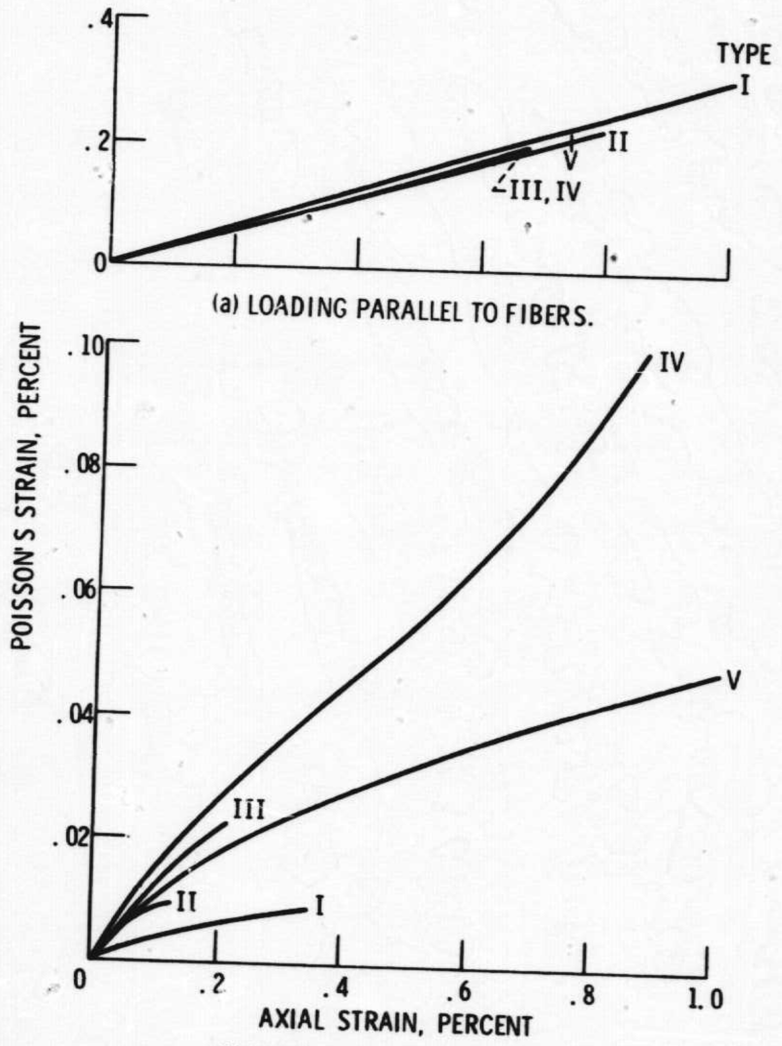

Figure 5. - Poisson's strain for smooth tensile specimens.

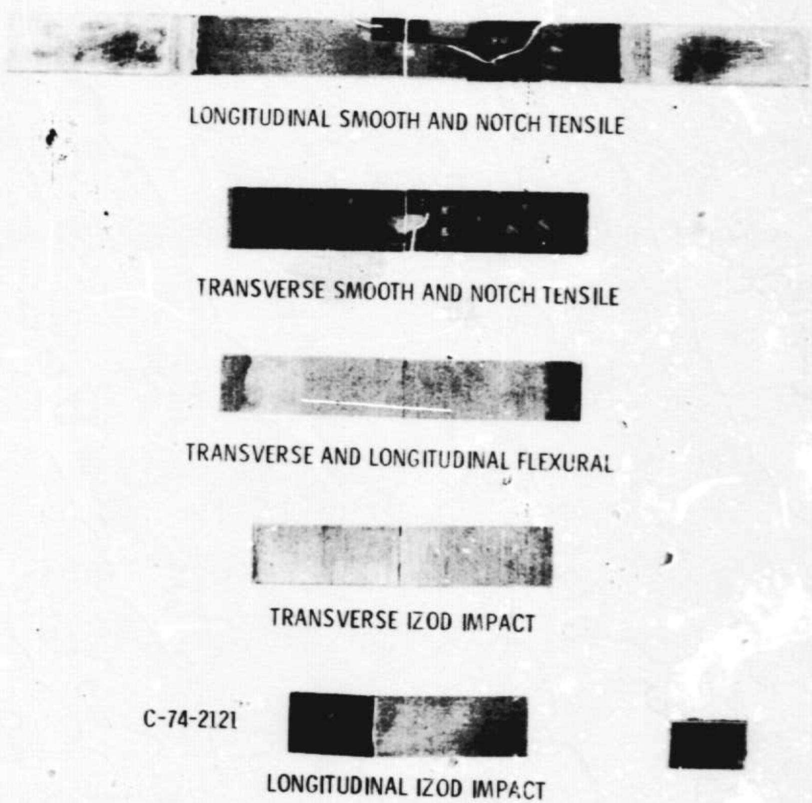

Figure 6. - Photographs of various fractured composite specimens.