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Completion of Evaluation of Manufacturing Processes for B/Al Composites Containing 0.2-mm-Diameter Boron Fibers

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COMPLETION OF EVALUATION OF MANUFACTURING PROCESSES FOR B/Al COMPOSITES CONTAINING 0.2-mm-DIAMETER BORON FIBERS

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SUMMARY

In Part II of a two-part program, four fabricators produced a total of 54 B/1100 Al, B/6061 Al, and B/2024 Al panels for evaluation. The eight-ply unidirectional, 45 to 50 volume percent, panels were made using 0.20-mm-diameter boron fibers which were obtained from a single supplier. About half the panels were made using fugitive binder tape and the remainder from dry woven tape. Hot press consolidation was carried out in vacuum except for one set of dry woven tape panels which were hot pressed in air. A single testing contractor conducted nondestructive inspection, metallography, fractography and mechanical property tests. The mechanical property tests included 21° and 260° C tensile tests and 21° C shear tests.

Panel quality, as measured by nondestructive evaluation, was generally good as were the 21° C tensile properties. The panels hot pressed in air, however, delaminated in the shear tests. Ultrasonic C-scan delineated these delaminated areas. Shear strength values were lower in these panels. But tensile strengths were not affected by the delaminations because of the relation between the tensile loading direction and the delaminations. Composite tensile strength was found to be proportional to the volume percent boron and the aluminum matrix rather than to the tape used or fabrication technique. Suitability of these composites for 260° C service was confirmed by tensile tests. Reproducibility of the tensile strengths of panels in Part II compared to those of Part I was very good for the B/6061 Al panels, fair for B/1100 Al and good for B/2024 Al panels. A recommendation is made to fabricate additional air hot pressed dry woven tape panels in order to more fully evaluate the most potentially cost-effective manufacturing process.

INTRODUCTION

A two-part study designed to evaluate the effect of manufacturing procedures on mechanical properties and cost of B/Al composite panels has been completed. The objective was to find ways to lower the cost of B/Al composites while retaining strength at least equivalent to that of current commercial B/Al products. It was shown in Part I (ref. 1) that B/Al panels can be fabricated with economical, 0.20-mm-diameter boron fibers with quality and strength comparable to composites containing 0.14-mm-diameter boron. From the five kinds of B/Al tape studied in Part I, two were selected for further evaluation in Part II: fugitive binder tape and dry woven tape. The former represents current manufacturing practice while the latter is more economically attractive because of shorter hot pressing time and the possibility of hot press consolidation in air.

This report covers Part II of the program in which a total of 54 B/Al panels were manufactured. Two fabricators used fugitive binder tape and the other two fabricators used dry woven tape. Testing and evaluation was similar to Part I, except that in Part II, elevated temperature tensile and room temperature shear tests were included. The more comprehensive Part II evaluation of the two most promising tapes was designed to verify the reproducibility of the Part I results and to provide a data base for these composites. Tensile strength was obtained at 260° C to determine material suitability for certain applications such as in turbine engines, and to evaluate the effect of processing on elevated temperature properties. Shear strengths were calculated from shear tests parallel to the boron fibers. The mode of failure was useful in evaluating the integrity at the Al/Al and Al/B interfaces.

MATERIALS AND FABRICATION

The B/Al composite panel fabrication and evaluation program is shown in table I. Boron fibers were produced by Composite Technology, Incorporated (CTI), the same basic organization that produced the fibers used in Part I of this program.* Continuous 0.2-mm-diameter boron fibers were produced by hydrogen reduction of boron trichloride on a 13-μm-diameter tungsten wire substrate.

Two fabricators, Amercom Incorporated (AI) and DWA Composite Specialties, Incorporated (DWA) were supplied with spooled boron fibers. Fugitive binder tape was produced by a process in which the boron fibers are aligned on an aluminum backing foil and held in place by a fugitive binder (organic resin). The binder is designed to burn off completely, prior to consolidation by hot pressing. Overall processing time in the furnaces includes in-process control requirements for each fabricator related to heating rates and outgassing cycles prior to consolidation. These outgassing data are not shown here. But the parameters used by AI and DWA in the vacuum hot press consolidation are shown in table II.

CTI provided the other two fabricators, TRW Incorporated (TRW) and United Technologies, Hamilton Standard Division, (UT), with dry woven tape. As shown in figure 1, this dry woven tape product was available in the form of broad goods 122 by 762 cm with the fibers aligned in the 122 cm direction. The boron fibers were cross woven with 20 by 300 μm 5056 Al ribbon, four ribbons per cm. Since there is no binder, the dry woven tape package is heated directly to the hot press consolidation temperature with alignment of the boron fibers maintained by the cross woven 5056 Al ribbons. The hot pressing parameters used by TRW and UT are also presented in table II. Note that TRW pressed in vacuum and UT used an air environment.

Six composite panels 2 by 254 by 305 mm were produced for nine combinations of tape, aluminum matrix alloy and fabrication procedure (table I). These 54 panels were made with an eight-ply layup of unidirectional fibers. Specified volume percent of fibers was 45 to 50.

Because of out-of-flatness problems and problems with resistance heaters within their ceramic dies, UT repeated the hot press consolidation cycle for 7 of 12 panels (table III). These reruns were made on the basis

*CTI was formerly known as Composite Materials Corporation.

of flaws indicated by ultrasonic C-scan examination by UT. However, no improvement in C-scan quality was noted by UT for the reprocessed panels.

EVALUATION PROCEDURES

The testing program conducted at Martin Marietta Corporation is outlined in table I. Determinations of panel flatness and liquid penetrant, X-ray, and ultrasonic inspections were made as described in reference 1.

Panel Layout and Cutting

Each panel was identified with a code (table I) and scribed with the specimen layout as shown in figure 2. The code consisted of a prefix for the panel followed by the test specimen identification. Example: The specimen AF7-L260-2 was taken from panel number AF7 for longitudinal tensile testing at 260° C. The last digit indicates specimen number 2 taken from the location shown in figure 2. Individual specimens were wet cut from the panels using a 254-mm-diameter diamond-impregnated cutting wheel and a specially designed cutoff table (ref. 1). No attempt was made to avoid (or include) flawed areas as determined by NDI when cutting the test specimens. But it was noted when specimens were taken from areas that included flaws.

Composite Tensile Tests

For the room temperature longitudinal tensile tests, 2024-T3 Al end tabs were adhesive bonded to the tensile blanks as shown in figure 3. Fiberglass-phenolic end tabs rather than matching aluminum alloy tabs were used for longitudinal tensile testing at 260° C for convenience. Tabs were not used for either room temperature or 260° C transverse tests.

To determine elastic moduli the tensile specimens were instrumented with a mechanical extensometer. For testing at 260° C the extensometer was insulated to minimize heat effects. Average loading rates were approximately 2500 MPa/min for longitudinal tests and 200 MPa/min for the transverse tests. A load/strain curve was plotted for each specimen from which the elastic moduli and ultimate strengths were computed. A quartz lamp clam shell furnace was used to heat the elevated temperature test specimens.

Composite Shear Tests

The shear test, illustrated in figure 4, produced shear loading parallel to the boron fibers. Although this steel loading block arrangement with serrated grip faces produced satisfactory results, hole boring of the B/Al test specimens with a 12.7-mm-diameter diamond-core drill was too time consuming. Therefore, in the early stages of shear testing, the test procedure was altered. In the modified procedure the shear specimens were sandwiched between the loading blocks and compressed with sufficient force in a testing machine to impart grip face marks on the composite specimen surface similar to the indentations that were produced by the bolting procedure. C-clamps were used to hold the loading blocks in place during testing. This procedure proved to be highly successful in the balance of the shear testing program.

Average loading rate in compression, to apply the shear load, was approximately 100 MPa/min. A load-deflection curve was plotted for each specimen from which shear strength was computed from the peak load.

Boron Fiber Tests

Boron fibers were removed from the composites by selective dissolution of the aluminum matrix in a 0.2 N sodium hydroxide solution. The fibers were then adhesive bonded to steel loading washers. The bonding area on these washers was sufficient to insure failure within a 152 mm gage length.

Twenty boron fibers were tested at 21° C for each composite panel to determine the tensile strength in the processed condition.

Fractography

Two typical fractures of tensile specimens from each panel (one longitudinal, one transverse) were examined on a scanning electron microscope (SEM). During SEM examination, any evidence of aluminum-aluminum delamination or aluminum-boron separation or transverse cracking in the boron fibers was documented. All SEM examinations were performed at a magnification of 100.

Metallography

All specimens selected were cut using a diamond grit cutting wheel at predetermined locations (fig. 2) and mounted in a Bakelite thermoplastic material.

Fiber distribution and overall quality was determined at a magnification of 50, while the integrity at the aluminum-aluminum interface, aluminum-boron interaction, small matrix voids, and delaminated areas were examined at a magnification of 200. All boron volume percent measurements were made with the aid of an image analyzing computer.

RESULTS

Mechanical properties of individual composite test specimens, boron fiber strength data, volume percent boron determinations, and nondestructive inspection results are shown in table III. Average values for much of these data are shown in table IV.

Longitudinal Tensile Strength of Composites

Average tensile strength at 21° and 260° C of the B/Al panels is plotted against average volume percent boron and aluminum matrix as shown in figure 5. For the B/6061 Al and for B/2024 Al panels (upper scatterband), it is evident that tensile strength increases with increasing volume percent boron. The DWA and AI B/6061 Al fugitive binder panels are stronger than the dry woven tape B/6061 Al panels. But this effect is probably a function of volume percent boron rather than an effect of the kind of tape used.

The tensile strength versus volume percent boron plot in figure 5 for the B/1100 Al panels shows a wider scatterband than was observed for the B/6061 Al panels. But the trend of increasing panel strength with increasing volume percent boron is apparent. In the following paragraphs average tensile strengths at 21° and 260° C will be compared for the fabricators and for each type of composite: B/1100 Al, B/6061 Al, and B/2024 Al. A comparison will also be made of the properties of composite panels fabricated in Part I and Part II of the program.

B/1100 Al. - Average strengths of composite panels at 21° and 260° C are shown in table IV and plotted in figure 6. AI and DWA B/1100 Al panels were nearly equal in strength at 21° C (1190 and 1200 MPa). The UT panels were next strongest at 1140 MPa, and the TRW panels were weakest at 1030 MPa. If the properties of the one UT panel (UW8 from table III) that was not subjected to multiple hot press consolidation cycles is considered typical, the 21° C tensile strength would be 1210 MPa rather than 1140 MPa. This shows the potential for the air hot pressed dry woven tape panel to be as strong as the fugitive binder panels made by AI and DWA.

At 260° C the average tensile strength of the DWA and UT panels were nearly identical (1080 and 1070 MPa, respectively). The AI panels were a little weaker at 1000 MPa. The TRW panels were still lower in strength (890 MPa). Average tensile strength at 260° C, compared to the strength at 21° C, decreased from 6 to 16 percent for the four kinds of panels (see figs. 5 and 6).

Photographs showing typical fractures (fig. 7) exhibit square, even fracture for the AI tests (fugitive binder specimens AF8-2 and AF11-2). For these specimens the lack of boron pullout from the matrix indicates that chemical bonds were established between the boron fibers and the matrix during hot press consolidation. Conversely, a major amount of fiber pullout was observed for DWA and UT specimens (dry woven specimens DF11-3, DF10-2, UW8-3, and UW 12-2). An intermediate amount of pullout was observed for the TRW panels (see dry woven specimens TW11-2 and TW12-2 in fig. 7). Scanning electron photomicrographs illustrating both even facture and boron fiber pullout are shown in figure 8.

B/6061 Al. - The DWA panels were strongest at 21° C (fig. 6) with an average tensile strength of 1590 MPa. The AI panels at 1400 MPa were next strongest. Strengths of the two dry woven tape panels were lower: 1240 MPa for TRW, and 1280 MPa for UT. If the four (of six) UT panels which were only hot press consolidated once (table II) were considered, the average strength of the UT panels would be notably improved to 1360 MPa.

Average tensile strength at 260° C varied from 1460 and 1370 MPa for the fugitive binder panels to 1250 and 1140 MPa for the dry woven tape panels (fig. 6). Average tensile strength at 260° C compared to 21° C strength decreased only 2 to 8 percent. This is about half the decrease observed for B/1100 Al panels.

The degree of boron fiber pullout from the matrices was less for the B/6061 Al than was observed previously for the B/1100 Al panels. AI and UT specimens (AF14-2, AF13-2, UW13-3, and UW18-1) (fig. 7) show very little pullout. For the others, DF13-3, DF14-2, TW18-1, and TW21-2, some boron pullout was evident.

B/2024 Al. - Average strength of these dry woven tape panels was similar to that of the dry woven tape TRW and UT B/6061 Al panels (fig. 6). At 21° C, the average strength was 1280 MPa. It dropped to 1220 MPa (5 percent) at 260° C.

Although the fractures of TW24-3 and TW24-2 have irregular surfaces, there was only slight evidence of boron fiber pullout (fig. 7).

Tensile Strength: Part I versus Part II

The four fabricators that made panels in groups of six for Part II used the same kind of tape and fabrication technique to produce the Part I panels in triplicate. A plot of the comparative 21° C strengths of Part I and Part II panels in figure 9, shows that weaker B/1100 Al panels were produced by three fabricators in Part II. Strength decreases were 13 percent for AI panels, 21 percent for DWA panels, and 28 percent for TRW panels. Conversely, the tensile strength of the UT panels was up 13 percent. The reasons for this lack of strength reproducibility for the B/1100 Al panels are not known.

Tensile strength reproducibility for the B/6061 Al panels, on the other hand, was quite good. Differences in Part 1 and Part II tensile strengths were less than 5 percent. The TRW B/2024 Al Part II panels exhibited 12 percent higher tensile strengths than the Part I panels.

Modulus of Elasticity for Composites

The longitudinal tensile specimens generally exhibited both a primary and secondary modulus of elasticity while the transverse specimens had only one modulus. The dual moduli result from the elastic-elastic and elastic-plastic interactions of the boron fibers and the aluminum alloy matrix in the longitudinal tests.

All modulus data are shown in table III. Average modulus values are shown in table IV except for the transverse 260° C test results. These latter modulus values are of questionable accuracy because of problems encountered with the elevated temperature fixtures.

The average longitudinal primary modulus data obtained at 21° and 260° C are shown in figure 10. The 21° C moduli for the B/1100 Al AI, DWA, and UT panels were similar (224 to 229 GPa). The modulus for the TRW panels was somewhat lower (191 GPa). At 260° C the moduli for the B/1100 Al panels decreased from 5 to 12 percent compared to the 21° C moduli.

For the B/6061 Al panels tested at 21° C, the moduli for the AI, DWA and UT panels were also similar (222 to 230 GPa). TRW panels, once again, had a considerably lower modulus (183 GPa). An exception to the rule of a reduction of modulus at elevated temperature was observed for the AI panels. The modulus at 260° C of 238 GPa was 7 percent higher than the 21° C modulus (fig. 10). A modest decrease in modulus of 4 to 7 percent was observed for the other three manufacturers' panels tested at 260° C.

The TRW B/2024 Al panels had a higher 21° C modulus than the TRW B/1100 Al and the B/6061 Al (198 GPa versus 191 and 183 GPa). As can be seen in figure 10, however, the 21° and 260° C moduli for the TRW B/2024 Al panels were lower than those obtained from the B/1100 Al and for the B/6061 Al panels of the other fabricators.

Secondary moduli values showed a pattern similar to that obtained for primary modulus (table IV).

Transverse Tensile Properties of Composites

B/1100 Al. - Transverse tensile strength at 21° C for the AI panels (99.1 MPa) was highest (fig. 11). TRW panels were next highest at (81.7 MPa) while the other panels, DWA (60.6 MPa) and UT (44.2 MPa) were considerbly weaker. A significant decrease in strength was observed in the elevated temperature tests, 37 to 41 percent compared to the 21° C tests (fig. 11).

Modulus values for both AI and DWA panels were identical at 21° C (118 GPa) (see table IV). The modulus values were slightly lower for UT panels (106 GPa) and for the TRW panels (104 GPa) (table IV).

B/6061 Al. - As shown in figure 11, the AI panels were strongest at 21° C (194 MPa). DWA (151 MPa) and TRW (146 MPa) panels had similar strengths, while the UT panels were lower (126 MPa). A reduction in strength of 21 to 38 percent was observed when testing was conducted at 260° C.

Modulus values for the fugitive binder panels at 21° C were 129 GPa for AI panels and 122 GPa for DWA panels (table IV). The dry woven tape panels had a somewhat lower moduli, 116 GPa for UT panels and 110 GPa for TRW panels (table IV).

B/2024 Al. - Figure 11 shows that the strength of a TRW dry woven tape panel at 21° C was slightly higher than the strongest B/6061 Al panel (200 MPa versus 194 MPa). Testing at 260° C reduced the strength of the B/2024 Al panel 23 percent.

At 21° C the average transverse modulus was 111 GPa (table IV).

Shear Tests of Composites

The following results include shear strengths and shear displacements for each specimen. A wide variation in the degree of shear displacement occurred for unknown reasons and some specimens bottomed out in the tooling. Photographs of typical tested shear specimens are shown in figure 12.

B/1100 Al. - Average shear strength and average displacement are shown in figure 13. The AI and TRW panels show strength slightly higher than the shear strength of annealed 1100 Al from reference 2. In addition the average displacements are high (12.8 and 12.5 mm). The DWA and UT specimens were weaker and lower in average deformation.

B/6061 Al. - Figure 13 shows that panels from all of the fabricators had higher shear strength than that of annealed 6061 Al (ref. 2), with AI having the highest strength 131 MPa and low (2.3 mm) deformation.

B/2024 Al. - The strength of these panels at 133 MPa (see fig. 13) was slightly higher than that of the strongest B/6061 Al panel and the annealed 2024 Al (ref. 2).

Delamination. - Delamination between plies and fiber pullout from the matrix was noted for the UT panels (table III). A photomicrograph of a tested specimen showing major delamination and fiber pullout from the matrix is shown in figure 14. Specimens from all six of the UT B/1100 Al panels exhibited this condition. Of the six UT B/6061 panels, two showed delaminations. The specimens that were delaminated on testing generally failed at lower loads and at smaller amounts of deformation (table III).

The delamination/fiber pullout condition was not observed for the AI, DWA, and TWA panels.

Tensile Strength of Fibers

For 142 spools of boron fibers with an average diameter of 0.201 mm, CTI reported an average tensile strength of 3790 MPa. It was found that all fabrication processes reduced the room temperature tensile strength of the fibers. The average tensile strength of processed boron fibers obtained from the 54 panels varied from 2740 to 2340 MPA (table IV). This represents a reduction in strength of from 28 to 38 percent. Hot press consolidation of dry woven tape in air resulted in less reduction in strength i.e., only a 30 percent reduction from the strength of unprocessed fibers for both B/1100 Al and B/6061 Al composites. The reason for this effect is not known.

Nondestructive Evaluation

Ultrasonic C-scan indications correlated well with areas of delamination in the shear tests. These delaminations were only severe in the UT panels. No correlation was observed, however, between C-scan indications and tensile strength (tables III and IV). All other kinds of nondestructive inspection showed no noteworthy flaws.

DISCUSSION

Fifty-four B/Al composite panels were successfully fabricated by four companies using 0.20-mm-diameter boron fibers. B/1100 Al and B/6061 Al panels were fabricated from both fugitive binder and dry woven tape, and B/2024 Al panels were fabricated from only dry woven tape. The most obvious single factor affecting longitudinal tensile strength, besides matrix alloy was volume percent boron. Other factors such as fabricator and kind of tape used, appeared to be of secondary importance. Thus, B/1100 Al and B/6061 Al panels made from fugitive binder tape with 46.9 to 49.9 volume percent boron were stronger than corresponding dry woven tape panels which contained 44.3 to 46.6 volume percent boron. Transverse tensile strength of the panels was, of course, a function of the matrix alloy, and the TRW B/2024 panels were strongest. It is worthy of note, however, that the AI B/1100 Al and B/6061 Al panels were strongest in each of these matrix groups in the transverse tests.

Tensile tests showed that the B/Al composite panels are serviceable at 260° C. For the B/1100 Al panels, the longitudinal tensile strength at 260° C was 16 percent (or less) below the 21° C values. For B/6061 Al and B/2024 Al panels, the reduction was 8 percent (or less). In the transverse direction, the 260° C tensile strength was up to 41 percent less than the 21° C values.

Through-the-thickness shear tests essentially tested the aluminum matrix parallel to the boron fibers. The manner in which the specimens failed was also of interest. For example, the UT shear specimens which had major C-scan indications, showed major delaminations. Other specimens without C-scan indications showed no delaminations even though large amounts of defomation were produced.

Reproducibility of longitudinal 21° C tensile strength between the panels of Part I and Part II was quite good (<6 percent difference) for the B/6061 Al panels. The reason for the lower strength of most B/1100 Al panels, up to 27 percent for Part II, is unknown. The reason for the increased strength ofthe B/2024 Al panels (11 percent) in Part II is also unknown.

Reduction in boron raw material cost and development of less costly fabrication methods were of primary importance in this study. The, raw material cost reductions was handled by the exclusive use of 0.20-mm-diameter boron in place of conventional 0.14 mm. A potential 10 percent raw material cost reduction is anticipated. The use of dry woven tape and hot pressing in air has potential for significant reduction in fabrication costs. The exact amount depends on the specific design of the composite part and the production quantity. Dry woven tape is easy to handle and the lack of a binder greatly decreases hot pressing time. Air hot pressing rather than vacuum hot pressing offers further savings.

Because of these potential cost reduction advantages, the equipment problems that UT encountered were unfortunate. Five of six B/1100 Al panels and two of B/6061 Al panels were exposed to more than one hot press consolidation cycle. Therefore, dry woven tape consolidated in air, was evaluated in a nonoptimum consolidation condition.

CONCLUDING REMARKS

In Part I of this program B/Al panels were successfully fabricated using 0.20-mm-diameter boron fibers. Quality and strength were found to be comparable to those of 0.14-mm-diamter B/Al composites. This report has dealt with Part II of the programs with more extensive evaluation of 0.20-mm-diameter B/Al panels. For Part II, two fabricators successfully produced panels using fugitive binder tape and two other fabricators successfully made panels using dry woven tape. Volume percent boron was related to tensile strength of the composites. Thus, the panels made from fugitive binder tape were generally stronger than those made from dry woven tape because the former had a higher volume percent boron. Longitudinal tensile strengths at 260° C followed the same pattern as the 21° C tests. Since only a moderate weakening effect was observed, these B/Al composites are candidate materials for elevated temperature applications. The shear tests proved to be of value in identifying delaminated areas in the panels that were hot press consolidated in air. These delaminations, which were observed in C-scan examination, could not be clearly associated with either the multiple hot press cycles or to the air hot pressing.

In order to more fully evaluate the most cost-effective manufacturing procedure, additional B/Al panels should be fabricated using dry woven tape and hot press consolidation in air. At least two fabricators should be employed as possible sources. In the B/Al composite, 50 volume percent boron should be maintained rather than the typical 45 percent which was achieved in this program.

REFERENCES

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TABLE I. - B/Al COMPOSITE PANEL FABRICATION AND EVALUATION PROGRAM

[0.20-mm-diam. boron fibers; 45/50 vol%; unidirectional; eight ply.]

A. Raw materials
  1. Boron fiber supplier: Composite Technology, Incorporated (CTI)
  2. Al matrix materials: 1100 Al, 6061 Al, 2024 Al
  3. B/Al tapes: Fugitive binder, dry woven

B. Manufacuring of panels (2 mm by 254 mm by 305 mm)
  1. Fabricators
    a. Amercom Incorporated (AI)
    b. DWA Composite Specialties, Incorporated (DWA)
    c. TRW Incorporated (TRW)
    d. United Technologies, Hamilton Standard Division (UT)

  2. Hot pressed panels with identification codes (54 panels)

Fabricator	Tape	Pressing atmosphere	Panel codes		
			B/1100 Al	B/6061 Al	B/2024 Al
AI	Fugitive binder	Vacuum	AF7 to AF12	AF13 to AF18	------
DWA	Fugitive binder	Vacuum	DF7 to DF12	DF13 to DF18	TW22 to TW27
TRW	Dry woven	Vacuum	TW10 to TW15	TW16 to TW21	------
UT	Dry woven	Air	UW7 to UW12	UW13 to UW18	------

C. Testing: Martin Marietta Corporation
  1. Nondestructive
    a. Ultrasonic C-scan
    b. Radiography
    c. Visual (general)
    d. Liquid penetrant

  2. Mechanical
    a. Tensile properties of composite at 21° and 260° C
    b. Shear properties of composite at 21° C
    c. Boron fiber strength as-received and processed

  3. Fractography of composite tensile test specimens

  4. Volume percent boron determinations

TABLE II. - HOT PRESSING PARAMETERS FOR EIGHT-PLY B/Al PANELS

Kind of tape	Aluminum matrix alloy	Hot pressing		Nominal temperature, °C	Pressure, MPa	Time, min
		Fabricator	Atmosphere			
Fugitive binder	1100	AI	Vacuum	560	31.1	40
		DWA	Vacuum	580	31.1	7
	6061	AI	Vacuum	530	31.1	30
		DWA	Vacuum	545	31.1	10
Dry woven	1100	TRW	Vacuum	495	68.9	40
		UT	Air	545	34.4	10
	6061	TRW	Vacuum	495	68.9	40
		UT	Air	545	34.4	10
	2024	TRW	Vacuum	480	68.9	40

TABLE III. - TEST DATA SUMMARY

Panel code and specimen number	Mechanical properties											
	Modulus of elasticity, GPa						Ultimate tensile strength, MPa				In-plane shear	
	Longitudinal				Transverse		Longitudinal		Transverse		Strength, MPa	Displacement, mm
	Primary		Secondary									
	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C		
AF7-1	213	194	198	---	105	171	1340	849	95.8	50.8	68.9	16.5
AF7-2	239	216	210	---	107	150	1200	1000	101	70.3	66.5	7
AF7-3	218	---	197	---	131	---	1210	----	102	----	----	----
AF8-1	225	210	196	---	146	179	1150	998	101	61.8	71.0	18
AF8-2	222	207	198	---	107	196	1220	1140	101	63.5	71.0	10.5
AF8-3	211	---	189	---	107	---	1320	----	95.1	----	----	----
AF9-1	221	215	199	---	117	95.1	1200	985	93	61.4	67.8	18
AF9-2	229	203	199	---	130	126	1250	1110	101	60.6	66.9	14
AF9-3	231	---	203	---	127	-----	1230	----	101	----	----	----
AF10-1	230	208	197	---	123	-----	1170	848	103	59.9	67.0	14
AF10-2	234	229	201	---	114	165	1130	843	103	63.3	66.0	6.5
AF10-3	230	---	204	---	109	-----	1310	----	101	----	----	----
AF11-1	230	224	191	---	110	86.2	1120	931	93.1	63.3	64.9	16.5
AF11-2	199	213	181	---	112	-----	1070	1040	91.7	66.2	62.7	5
AF11-3	202	---	184	---	127	-----	1020	----	103	----	----	----
AF12-1	225	213	194	---	105	175	1020	1190	101	59.2	65.5	14
AF12-2	234	212	197	---	115	112	1140	1100	95.1	64.6	67.7	14
AF12-3	237	---	212	---	137	-----	1230	----	102	----	----	----
AF13-1	231	256	197	---	127	127	1460	1360	190	154	132	1.5
AF13-2	220	244	179	---	120	112	1420	1460	203	151	126	1.5
AF13-3	219	---	188	---	124	-----	1460	----	203	-----	-----	----
AF14-1	222	236	201	---	130	168	1320	1400	199	168	134	2
AF14-2	238	240	200	---	123	-----	1340	1520	183	145	128	2
AF14-3	225	---	201	---	134	-----	1360	----	197	----	-----	----
AF15-1	223	---	190	---	121	161	1420	----	172	154	127	3
AF15-2	229	259	193	---	126	101	1270	1420	192	150	139	3
AF15-3	225	---	195	---	129	-----	1430	----	177	-----	-----	----
AF16-1	220	243	192	---	134	-----	1410	1370	192	167	112	0.5
AF16-2	219	232	196	---	138	15	1310	1430	191	133	121	1.5
AF16-3	215	---	203	---	128	-----	1520	----	207	-----	-----	----

FOR B/Al PANELS

Processed boron fiber strength, MPa			Boron fibers, vol %	Nondestructive inspection indications					
				Flatness Δh, mm	Thickness, mm		Liquid pene-trant	X-ray	Ultrasonic C-scan indication area, percent
Minimum	Maximum	Average			Average	Variation			
1730	3280	2820	48.4 53.4 48.2	1.24	1.95	0.076	S.P.	S.M.I. M.F. -----	<1
2110	2940	2600	52.4 51.7 52.1	1.22	1.93	0.051	S.P.	M.F.	<1
1050	3250	2620	47.2 45.8 50.0	0.686	1.93	0.076	S.P.	M.I. M.F. -----	0
2320	3370	3140	50.9 51.8 49.6	1.09	1.94	0.025	S.P.	M.I. M.F. -----	<1
1700	3220	2540	45.7 44.7 48.2	0.889	1.91	0.076	S.P.	S.M.I. M.F. -----	<1
1300	3309	2450	47.6 26.7 45.4	1.02	1.93	0	S.P.	L.F.D. M.I. -----	<1
1890	3320	2550	44.9 45.0 44.6	0.889	1.98	0.051	S.P.	M.I. M.F. -----	<1
1480	3080	2440	46.9 44.6 49.5	2.11	1.98	0.025	S.P.	M.I. M.F. -----	<1
1720	3340	2730	47.7 48.0 48.4	0.457	1.97	0.025	S.P.	M.F.	<1
2140	3680	2890	47.1 46.8 48.9	3.10	1.97	0.025	S.P.	M.I. M.F. -----	<1

TABLE III.

Panel code and specimen number	Mechanical properties											
	Modulus of elasticity, GPa						Ultimate tensile strength, MPa				In-plane shear	
	Longitudinal				Transverse		Longitudinal		Transverse		Strength, MPa	Displacement, mm
	Primary		Secondary									
	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C		
AF17-1	221	238	197	---	130	89.6	1410	1300	199	152	125	2
AF17-2	210	221	193	---	130	95.1	1410	1280	194	150	135	2.5
AF17-3	217	---	192	---	130	-----	1470	----	202	-----	-----	---
AF18-1	222	232	193	---	125	161	1330	1100	199	156	148	5
AF18-2	219	214	193	---	133	165	1360	1470	192	157	139	3
AF18-3	219	---	199	---	137	-----	1480	----	197	-----	-----	---
DF7-1	---	189	184	---	150	101	1180	1080	62.1	40.4	55.9	4
DF7-2	---	204	186	---	111	161	1160	1120	72.4	38.4	48.5	3
DF7-3	214	---	176	---	125	-----	1210	----	53.8	----	-----	---
DF8-1	207	172	187	---	100	133	1350	1170	55.2	33.6	71.7	5.5
DF8-2	214	182	193	---	123	114	1410	1210	52.4	37.0	53.5	3
DF8-3	214	---	190	---	114	-----	990	----	51.0	----	-----	---
DF9-1	236	---	187	174	117	201	1250	1110	53.1	29.5	61.0	5.5
DF9-2	231	188	193	168	116	-----	1090	921	53.1	31.4	41.9	1.5
DF9-3	218	---	197	---	126	-----	1260	----	51.7	----	-----	---
DF10-1	217	---	181	204	112	201	1230	1050	55.2	33.7	63.0	8.5
DF10-2	276	207	205	182	112	203	1200	1080	69.6	35.4	50.0	3.5
DF10-3	---	---	179	---	116	-----	1280	----	66.2	----	-----	---
DF11-1	224	---	183	---	111	-----	1200	1050	69.6	42.1	-----	---
DF11-2	239	228	201	183	119	100	1240	1040	79.3	39.8	52.9	4
DF11-3	220	---	186	---	112	-----	1150	----	60.7	----	-----	---
DF12-1	---	---	177	195	119	76.5	1060	1020	55.2	34.6	-----	---
DF12-2	263	242	202	183	116	73.7	1090	1080	71.7	35.4	46.1	1
DF12-3	---	---	183	---	133	-----	1200	----	57.9	----	-----	---
DF13-1	223	180	183	---	152	223	1420	1380	177	127	94.6	3
DF13-2	210	234	175	---	86.2	145	1480	1380	123	123	129	3
DF13-3	218	---	195	---	93.1	-----	1460	----	120	-----	-----	---
DF14-1	221	205	190	---	119	157	1720	1510	176	105	97.2	1.5
DF14-2	244	210	200	---	130	-----	1720	1420	146	100	105	2
DF14-3	---	---	199	---	121	-----	1710	----	133	-----	-----	---

- Continued.

				Nondestructive inspection indications					
Processed boron fiber strength, MPa			Boron fibers, vol %	Flatness Δh, mm	Thickness, mm		Liquid pene- trant	X-ray	Ultrasonic C-scan indication area, percent
Minimum	Maximum	Average			Average	Variation			
1890	3030	2420	45.7 47.7 49.7	1.78	1.97	0.025	S.P.	M.I. M.F. ----	<1
1310	3340	2680	45.7 43.5 49.1	1.57	1.98	0.025	S.P.	M.I. M.F. ----	<1
1450	2290	2100	49.1 47.8 48.7	3.00	2.29	0.051	S.P.	S.M.I.	1
1190	3120	2580	46.8 48.1 46.0	0.635	2.32	0.051	S.P.	S.F.B.	1
1120	2510	2140	50.0 49.2 48.7	2.29	2.28	0.051	S.P.	L.F.D. S.M.I. ------	<1
1750	2920	2370	49.9 50.1 50.6	2.49	2.29	0.051	S.P.	L.F.D. S.M.I. ------	<1
1180	2740	2380	48.3 46.8 51.3	3.05	2.30	0.051	S.P.	L.F.D. S.M.I. ------	<1
2150	2790	2460	47.1 50.1 52.1	1.85	2.30	0.025	S.P.	S.M.I. S.F. ------	<1
1580	3140	2590	51.8 47.5 50.0	2.34	2.21	0.203	S.P.	L.F.D. S.M.I. ------	30
1760	3100	2540	47.7 47.1 48.4	4.14	2.16	0.076	S.P.	L.F.D. S.M.I. ------	25

TABLE III.

Panel code and specimen number	Mechanical properties											
	Modulus of elasticity, GPa						Ultimate tensile strength, MPa				In-plane shear	
	Longitudinal				Transverse		Longitudinal		Transverse		Strength, MPa	Displacement, mm
	Primary		Secondary									
	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C		
DF15-1	252	212	203	---	125	123	1710	1350	145	96.5	-----	----
DF15-2	---	210	202	---	129	-----	1650	1370	155	93.8	101	2
DF15-3	248	---	181	---	124	-----	1620	----	163	-----	-----	----
DF16-1	---	209	200	---	117	130	1680	1590	147	137	101	2
DF16-2	228	243	203	---	136	-----	1710	1340	164	121	120	2
DF16-3	227	---	203	---	108	-----	1490	----	136	-----	-----	----
DF17-1	265	215	216	---	125	163	1570	1440	163	131	105	1
DF17-2	236	231	203	---	132	177	1530	1600	152	121	110	2
DF17-3	---	---	191	---	143	-----	1330	----	159	-----	-----	----
DF18-1	209	224	190	---	119	-----	1650	1550	145	128	88.9	1
DF18-2	214	203	197	---	112	92.4	1590	1590	155	117	115	3.5
DF18-3	221	---	195	---	128	-----	1490	----	163	-----	-----	----
TW10-1	190	141	149	---	113	-----	1130	1110	85.5	48.3	67.7	9
TW10-2	---	160	143	---	110	185	1180	1060	85.5	54.1	67.5	12.5
TW10-3	181	---	---	---	87.6	-----	1190	----	86.9	-----	-----	----
TW11-1	182	188	139	145	101	170	1060	904	74.5	51.1	67.0	9.5
TW11-2	186	182	141	137	101	121	943	783	80	51.4	64.3	10.5
TW11-3	188	---	145	---	112	-----	993	----	84.1	-----	-----	----
TW12-1	203	166	150	---	109	139	1060	983	80.0	52.3	67.8	10
TW12-2	179	156	152	---	101	168	1030	874	81.4	51.6	68.6	15
TW12-3	185	---	148	---	110	-----	1170	----	78.6	-----	-----	----
TW13-1	221	145	143	---	94.5	136	958	842	85.5	54.6	66.1	14
TW13-2	---	139	143	---	111	164	1150	794	87.6	53.3	66.0	8.5
TW13-3	---	---	143	---	93.8	-----	991	----	85.5	-----	-----	----
TW14-1	---	176	158	---	106	176	1040	721	77.3	47.8	66.7	10
TW14-2	190	154	153	---	112	185	1000	980	80.7	49.4	62.5	20
TW14-3	191	---	150	---	99.3	-----	1060	----	77.2	-----	-----	----
TW15-1	---	---	145	149	97.2	170	884	785	80.0	51.3	68.3	12.5
TW15-2	---	212	154	148	102	172	840	794	79.0	52.3	71.0	18
TW15-3	---	---	149	---	108	-----	910	----	81.0	-----	-----	----

- Continued.

Processed boron fiber strength, MPa			Boron fibers, vol %	Nondestructive inspection indications					
				Flatness Δh, mm	Thickness, mm		Liquid penetrant	X-ray	Ultrasonic C-scan indication area, percent
Minimum	Maximum	Average			Average	Variation			
2260	3090	2750	47.8 52.3 50.4	6.50	2.21	0.102	S.P.	S.M.I.	35
1680	2740	2250	48.2 50.5 49.2	3.66	2.19	0.025	S.P.	S.M.I.	15
1850	3590	3040	50.7 47.6 47.1	2.16	2.18	0.102	S.P.	F.B. S.M.I. ------	15
1720	3400	2480	50.6 49.0 50.6	1.80	2.15	0.051	S.P.	S.M.I.	15
1680	3390	2790	41.0 45.1 42.4	2.16	2.21	0.076	S.P.	L.F.D. F.B. S.M.I.	<1
1670	3500	2670	45.2 42.7 42.5	1.42	2.23	0.051	S.P.	L.F.D. S.M.I. ------	<1
2150	3140	2700	46.5 47.2 46.3	2.84	2.18	0.051	S.P.	L.F.D. F.B. S.M.I.	5
1810	3080	2460	44.7 45.8 43.8	1.55	2.29	0.051	S.P.	L.F.D. S.M.I. ------	<1
2340	3300	2920	45.2 44.3 46.5	2.29	2.16	0.025	S.P.	L.F.D. S.M.I. ------	1
2640	3200	2880	45.5 43.5 43.2	2.46	2.16	0.025	None	L.F.D. S.M.I. ------	1

TABLE III.

Panel code and specimen number	Mechanical properties											
	Modulus of elasticity, GPa						Ultimate tensile strength, MPa				In-plane shear	
	Longitudinal				Transverse		Longitudinal		Transverse		Strength, MPa	Displacement, mm
	Primary		Secondary									
	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C		
TW16-1	---	165	148	---	101	-----	1300	1190	140	102	87.6	2.5
TW16-2	---	168	145	141	110	-----	1260	1120	140	103	100	7
TW16-3	168	---	---	---	108	-----	1300	----	150	-----	-----	----
TW17-1	208	162	152	---	118	82.7	1220	1130	145	98.6	84.8	2
TW17-2	190	186	150	141	110	126	1340	1240	147	95.1	98.6	5.5
TW17-3	197	---	177	---	110	-----	1290	----	141	-----	-----	----
TW18-1	---	186	150	136	107	76.5	1360	1180	146	103	91.7	4
TW18-2	198	184	150	140	113	-----	1300	1270	150	104	95.8	3
TW18-3	172	---	155	---	114	-----	1330	----	148	-----	-----	----
TW19-1	185	168	147	---	107	95.1	847	1030	150	102	93.8	3.5
TW19-2	175	163	147	125	108	100	1160	918	150	101	100	6
TW19-3	168	---	148	---	108	-----	1160	----	153	-----	-----	----
TW20-1	---	152	133	121	96.5	86.9	1150	1130	150	101	97.9	6.5
TW20-2	160	140	134	---	108	123	1270	1060	142	96.5	94.5	5.5
TW20-3	---	---	142	---	105	-----	1270	----	143	-----	-----	----
TW21-1	---	190	144	125	115	110	1230	1210	147	99.3	98.0	5
TW21-2	---	171	149	139	114	101	1290	1180	146	114	100	7
TW21-3	187	---	154	---	126	-----	1330	----	139	-----	-----	----
TW22-1	171	177	150	---	109	103	1020	1020	194	159	121	1
TW22-2	205	193	150	139	110	110	1190	999	193	156	132	1.5
TW22-3	209	---	157	---	110	-----	1160	----	197	-----	-----	----
TW23-1	199	173	154	---	112	93.8	1470	1370	194	161	132	1.5
TW23-2	212	188	151	---	114	-----	1410	1320	199	149	146	3
TW23-3	178	---	152	---	118	-----	1450	----	200	-----	-----	----
TW24-1	190	228	163	---	110	91.0	1360	1440	201	155	134	1.5
TW24-2	188	190	158	---	113	107	1340	1310	201	150	129	1.5
TW24-3	206	---	170	---	109	-----	1500	----	183	-----	-----	----
TW25-1	165	177	151	---	105	117	1180	1300	205	156	125	1
TW25-2	---	202	158	---	118	-----	1150	1240	215	152	130	1
TW25-3	---	---	163	---	110	-----	1160	----	208	-----	-----	----

- Continued.

Processed boron fiber strength, MPa			Boron fibers, vol %	Nondestructive inspection indications					
				Flatness Δh, mm	Thickness, mm		Liquid pene-trant	X-ray	Ultrasonic C-scan indication area, percent
Minimum	Maximum	Average			Average	Variation			
1830	2930	2450	44.9 41.0 47.2	2.54	2.28	0.025	S.P.	L.F.D. S.M.I. ------	20
1940	2840	2490	43.8 43.6 43.0	1.78	2.31	0.025	S.P.	L.F.D. S.M.I. ------	5
2080	3590	2760	42.3 48.7 47.6	1.09	2.30	0.051	S.P.	L.F.D. S.M.I. ------	10
1390	3040	2400	44.9 46.3 43.8	1.60	2.33	0.025	S.P.	L.F.D. S.M.I. ------	5
1560	2830	2160	40.7 42.9 43.9	2.39	2.51	0.076	None	L.F.D. S.M.I. ------	5
1260	2760	2300	42.9 42.7 47.3	1.78	2.28	0.025	S.P.	L.F.D. M.I. ------	5
2360	3060	2720	42.1 47.0 45.3	1.65	2.22	0.025	S.P.	V.P.	5
2150	3360	2680	43.0 41.2 44.2	1.17	2.24	0.051	S.P.	None	10
1160	3570	2560	42.8 46.8 47.4	1.93	2.09	0.025	S.P.	S.M.I. S.F. ------	10
1790	2730	2260	46.7 48.8 48.0	2.03	2.08	0.025	S.P.	S.M.I.	20

TABLE III.

Panel code and specimen number	Mechanical properties													
	Modulus of elasticity, GPa						Ultimate tensile strength, MPa				In-plane shear	
	Longitudinal				Transverse		Longitudinal		Transverse		Strength, MPa	Displacement, mm
	Primary		Secondary									
	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C		
TW26-1	216	190	183	---	114	99.3	1320	1090	208	153	116	1
TW26-2	197	187	164	---	111	105	1300	1260	195	150	162	3
TW26-3	213	---	181	---	106	-----	1200	----	212	------	-----	----
TW27-1	219	188	165	---	111	117	1150	1110	199	150	125	1
TW27-2	191	183	162	---	119	108	1260	1240	194	165	141	1
TW27-3	214	---	161	---	107	-----	1370	----	194	------	-----	----
[a]UW7-1	197	218	167	---	122	-----	1260	912	44.4	36.6	53.2	5
[a]UW7-2	231	201	176	---	101	71.0	998	1120	41.4	36.2	[b]53.4	5.5
[a]UW7-3	206	---	174	---	100	-----	1200	----	41.9	------	-----	----
UW8-1	207	172	170	---	97.2	-----	1290	1050	39.5	9.51	64.8	10
UW8-2	225	230	179	---	101	-----	1100	1020	44.7	24.1	[b]35.5	3
UW8-3	229	---	185	---	99.3	-----	1250	----	47.1	------	-----	----
[c]UW9-1	209	205	181	---	121	-----	1080	1100	50.8	26.7	61.1	9
[c]UW9-2	228	195	172	---	117	-----	1120	1090	48.7	31.7	[b]64.5	8
[c]UW9-3	218	---	181	---	103	-----	964	----	41.9	------	-----	----
[a]UW10-1	332	202	186	---	103	-----	1080	1050	55.8	38.3	[d]42.3	4
[a]UW10-2	261	204	178	---	110	-----	1130	971	55.2	36.8	51.6	3
[a]UW10-3	---	---	177	---	126	-----	1130	----	53.8	------	-----	----
[a]UW11-1	223	216	178	---	101	199	1030	1090	35.5	13.1	65.3	7
[a]UW11-2	198	191	170	---	110	166	1230	1330	46.7	23.9	[b]21.0	5
[a]UW11-3	212	---	181	---	101	-----	1220	----	53.1	------	-----	----
[a]UW12-1	237	186	189	---	97.9	160	1170	999	27.9	8.48	52.5	7
[a]UW12-2	208	205	178	---	103	-----	1040	1110	30.3	21.1	[b]27.2	4.5
[a]UW12-3	205	---	174	---	99.3	-----	1150	----	36.2	------	-----	----

[a]Two hot pressing cycles.
[b]Major delamination during shear testing.
[c]Three hot pressing cycles.
[d]Some delamination during shear testing.

- Continued.

Processed boron fiber strength, MPa			Boron fibers, vol %	Nondestructive inspection indications					
				Flatness Δh, mm	Thickness, mm		Liquid pene- trant	X-ray	Ultransonic C-scan indication area, percent
Minimum	Maximum	Average			Average	Variation			
1620	3200	2590	42.6 46.9 44.7	2.95	2.14	0.051	S.P.	L.F.D. S.M.I. ------	20
1920	2530	2080	45.4 44.5 44.9	3.30	2.16	0.051	S.P.	M.I. S.F. ------	20
1250	3330	2610	42.0 44.0 43.5	1.98	1.87	0.025	---- C S.P.	F.C. S.M.I. S.F.	60
2140	2980	2610	44.3 44.0 46.5	2.92	1.91	0.051	---- D.S. S.P.	F.C. L.F.D. S.M.I.	70
1060	3310	2590	43.8 42.0 48.9	1.22	1.94	0.025	S.P.	F.C. L.F.D. S.M.I.	85
2300	2960	2650	48.7 46.8 45.6	1.24	1.91	0	---- D.N. S.P.	F.C.,S.F. L.F.D. S.M.I.,S.F.	95
1780	3060	2630	45.1 44.0 40.9	1.96	1.89	0.051	---- D.N. S.P.	F.C.,L.F.D. M.I. V.P.	75
2230	3200	2740	46.8 43.2 47.8	1.83	1.92	0.025	S.P.	F.C. L.F.D. S.M.I.,M.I.	80

TABLE III.

Panel code and specimen number	Mechanical properties											
	Modulus of elasticity, GPa						Ultimate tensile strength, MPa				In-plane shear	
	Longitudinal				Transverse		Longitudinal		Transverse		Strength, MPa	Displacement, mm
	Primary		Secondary									
	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C	21° C	260° C		
UW13-1	213	224	182	---	122	193	1110	1120	128	82.0	95.8	11
UW13-2	221	185	180	---	118	-----	932	1140	125	84.1	-----	----
UW13-3	229	---	185	---	122	-----	1170	----	134	----	-----	----
UW14-1	202	206	179	---	106	-----	1380	1370	101	73.8	85.5	4
UW14-2	255	192	175	---	117	-----	1460	1420	103	68.9	92.4	8
UW14-3	232	---	173	---	117	-----	1390	----	107	----	-----	----
[a]UW15-1	216	254	185	184	96.5	-----	776	990	131	51.3	117	9
[a]UW15-2	210	243	185	174	108	95.1	1050	1040	129	79.3	[d]86.2	2
[a]UW15-3	228	---	177	---	112	-----	973	----	140	----	-----	----
UW16-1	292	225	194	---	118	-----	1280	1420	116	80.0	95.8	8
UW16-2	203	220	183	---	118	84.8	1480	1400	125	78.6	101	9
UW16-3	212	---	179	---	127	-----	1380	----	126	----	-----	----
UW17-1	---	172	175	---	112	-----	1560	1370	130	75.8	90.3	5.5
UW17-2	256	176	171	---	119	130	1640	1390	132	83.4	96.5	6.5
UW17-3	---	---	177	---	117	-----	1490	---	126	----	-----	----
[a]UW18-1	201	226	178	---	122	201	1310	1320	129	82.0	110	5
[a]UW18-2	197	249	173	172	119	112	1240	1050	140	97.2	[d]90.3	2.5
[a]UW18-3	199	---	174	---	112	-----	1330	----	143	----	-----	----

[a]Two hot pressing cycles.
[d]Some delamination during shear testing.

- Concluded.

				Nondestructive inspection indications					
Processed boron fiber strength, MPa			Boron fibers, vol %	Flatness Δh, mm	Thickness, mm		Liquid pene- trant	X-ray	Ultrasonic C-scan indication area, percent
Minimum	Maximum	Average			Average	Variation			
1050	3190	2590	45.0 44.9 46.3	0.737	1.86	0.025	S.P.	F.C. S.M.I. ------	5
2140	2830	2450	45.7 46.8 44.9	0.914	1.83	0	S.P.	F.C. S.M.I. M.I.	100
1410	3000	2230	44.9 48.1 43.5	3.07	1.84	0.025	D.S. S.P. ----	F.C.,L.F.D. S.F. S.M.I.	50
2300	3230	2760	47.2 48.4 48.5	1.19	1.85	0.025	S.P.	F.C. M.I. ------	60
1560	3670	3080	44.4 48.1 49.4	0.940	1.83	0.025	S.P.	F.C. M.I. V.P.	40
2260	3300	2760	48.8 46.7 47.1	2.27	1.86	0.051	---- D.S. S.P.	F.C. L.F.D. S.M.I.	30

TABLE IV. - AVERAGE TEST DATA FOR B/Al PANELS

Kind of tape	Aluminum matrix alloy	Hot pressing		C-scan indication area, average percent	Average boron, vol %	Average processed boron fiber strength, MPa	Average modulus of elasticity, GPa					Average ultimate tensile strength, MPa				Average in-plane shear	
		Fabricator	Atmosphere				Longitudinal				Transverse	Longitudinal		Transverse		Strength, MPa	Deformation, mm
							Primary		Secondary								
							21° C	260° C	21° C	260° C	21° C	21° C	260° C	21° C	260° C		
Fugitive binder	1100	AI	Vacuum	<1	48.9	2700	224	212	197	---	118	1190	1000	99.1	62.1	67.2	12.8
		DWA	Vacuum	<1	48.9	2340	229	202	188	184	118	1200	1080	60.6	35.9	54.4	4.0
	6061	AI	Vacuum	<1	46.9	2620	222	238	195	---	129	1400	1370	194	153	131	2.3
		DWA	Vacuum	23	49.3	2610	230	215	196	---	122	1590	1460	151	117	106	2.1
Dry woven	1100	TRW	Vacuum	<2	44.5	2740	191	165	147	145	104	1030	890	81.7	51.5	67.0	12.5
		UT	Air	78	44.9	2640	225	202	178	---	106	1140	1070	44.2	26.1	49.4	5.9
	6061	TRW	Vacuum	8	44.3	2430	183	170	149	134	110	1240	1140	146	102	95.2	4.8
		UT	Air	48	46.6	2650	223	214	179	177	116	1280	1250	126	78.0	96.4	6.4
	2024	TRW	Vacuum	14	45.1	2480	198	190	161	139	111	1280	1220	200	155	133	1.5

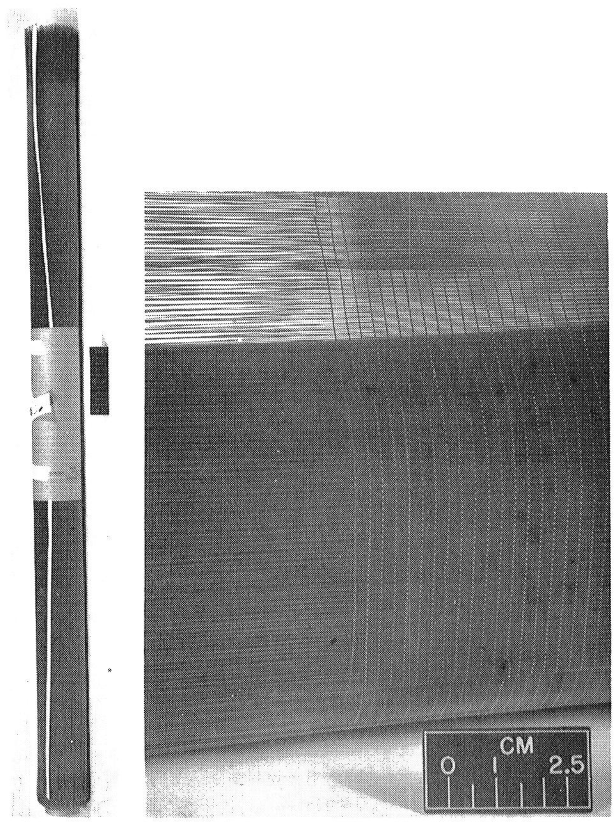


Figure 1. - Roll of dry woven tape broad goods 122 cm x 762 cm. Boron fibers 0.20 mm diam cross woven with 20 μm x 300 μm 5056 Al ribbon, four ribbons per cm.

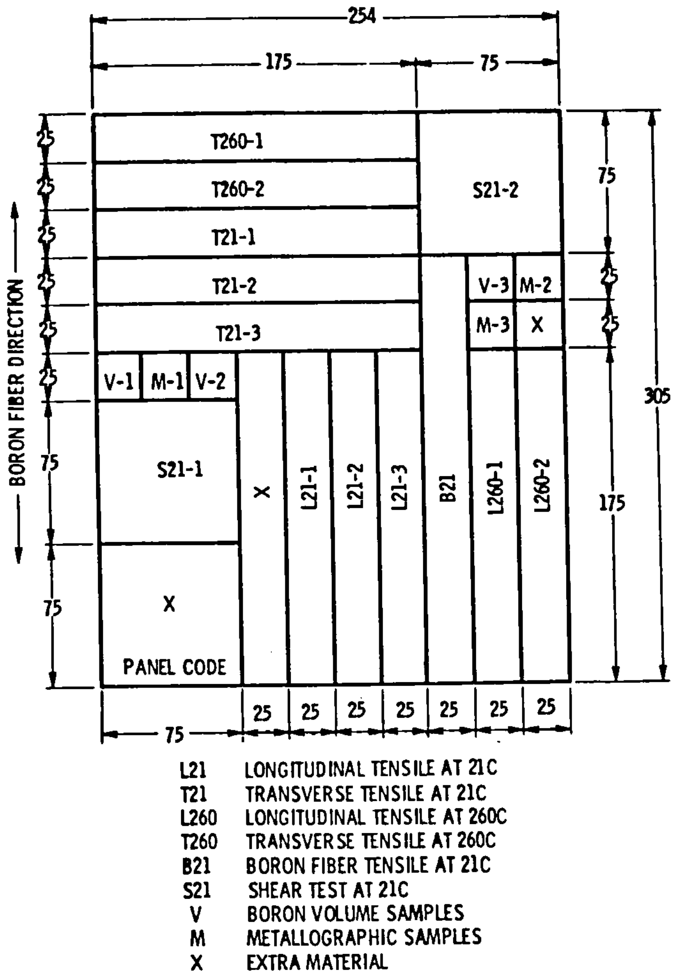


Figure 2. - Test specimen layout for boron/aluminum composite panels. (Dimensions are in mm.)

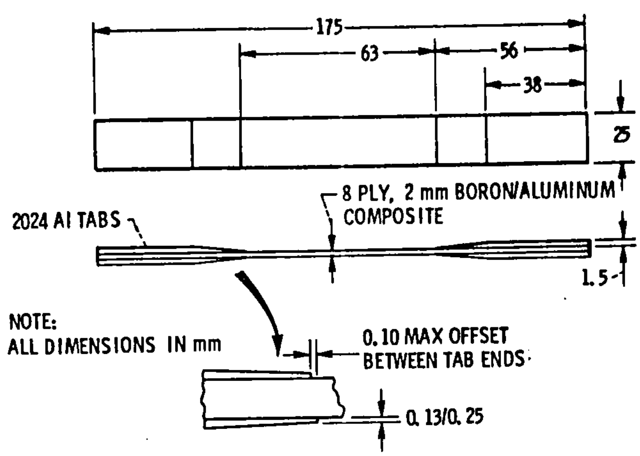
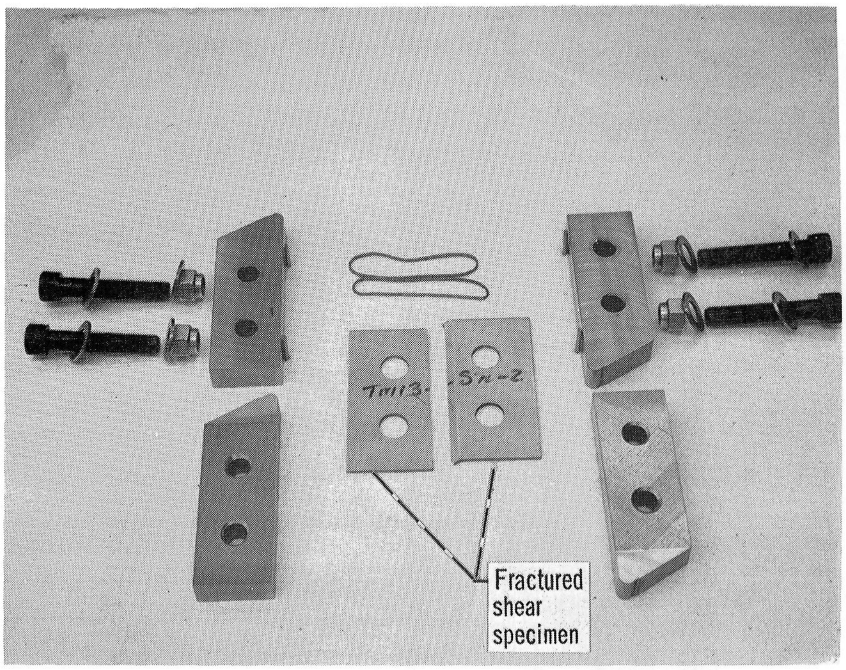
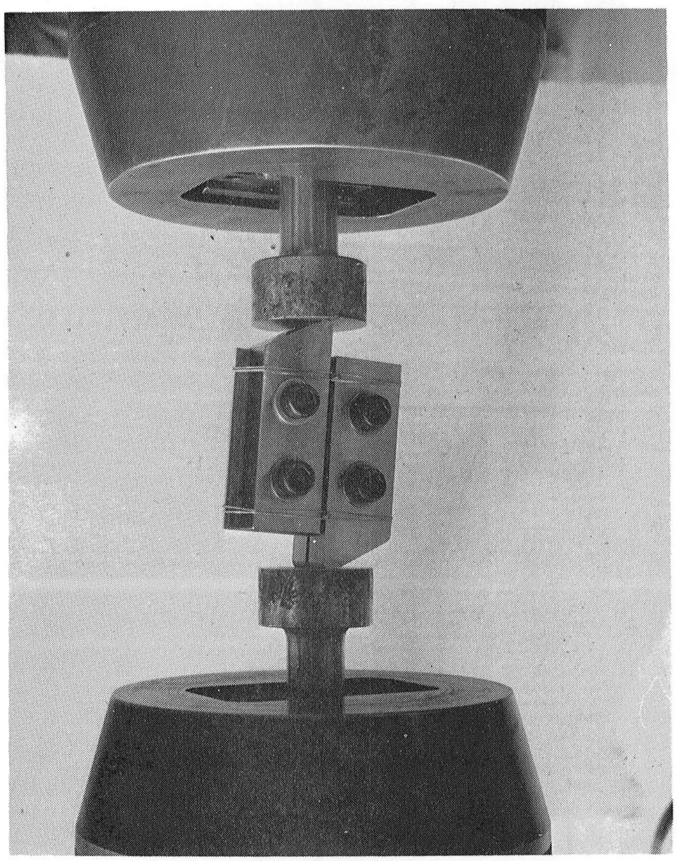


Figure 3. - Straight sided boron/aluminum tensile test specimen with end tabs.

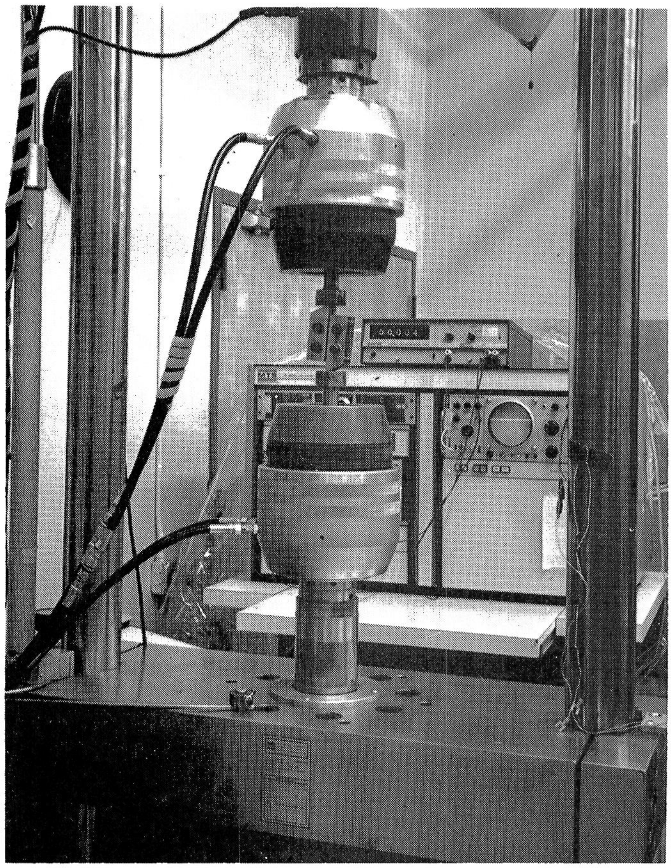


(a) Tested specimen and block supports.



(b) Clamp arrangement.

Figure 4. - Composite shear test details.



(c) Test machine.

Figure 4. - Concluded.

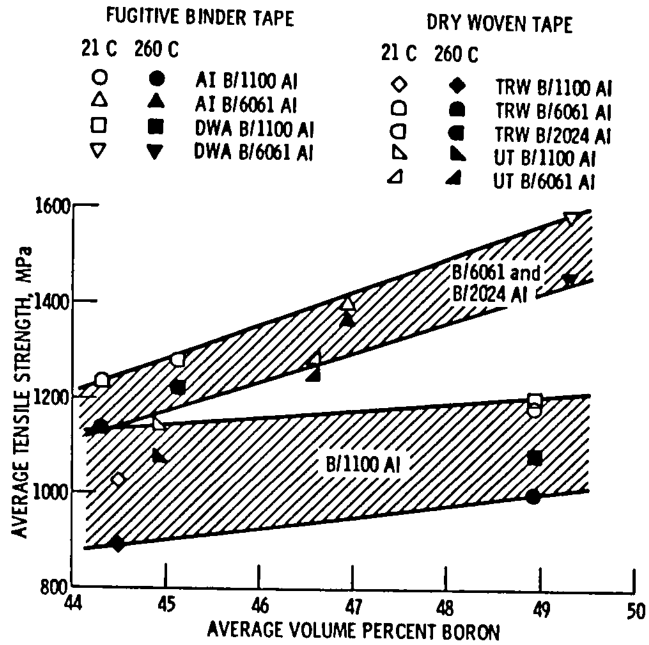


Figure 5. - Effect of volume percent boron on longitudinal tensile strength for B/Al composite sheet at 21° C and at 260° C.

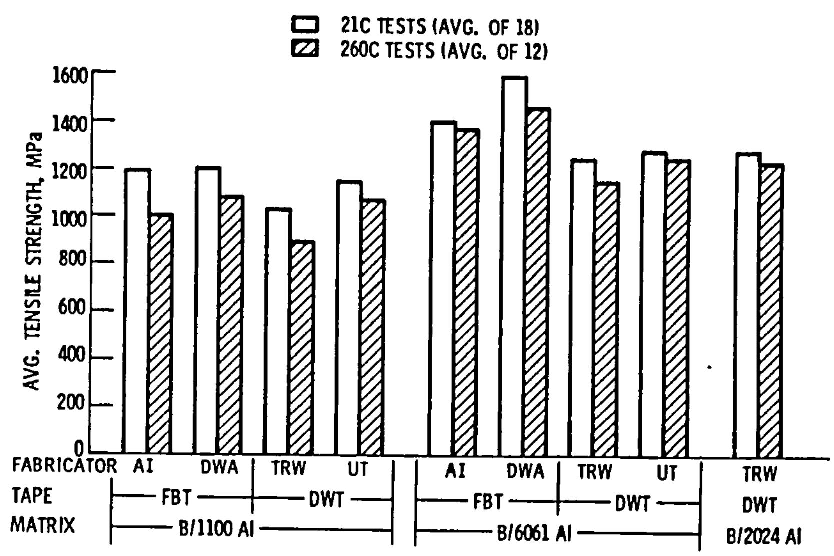
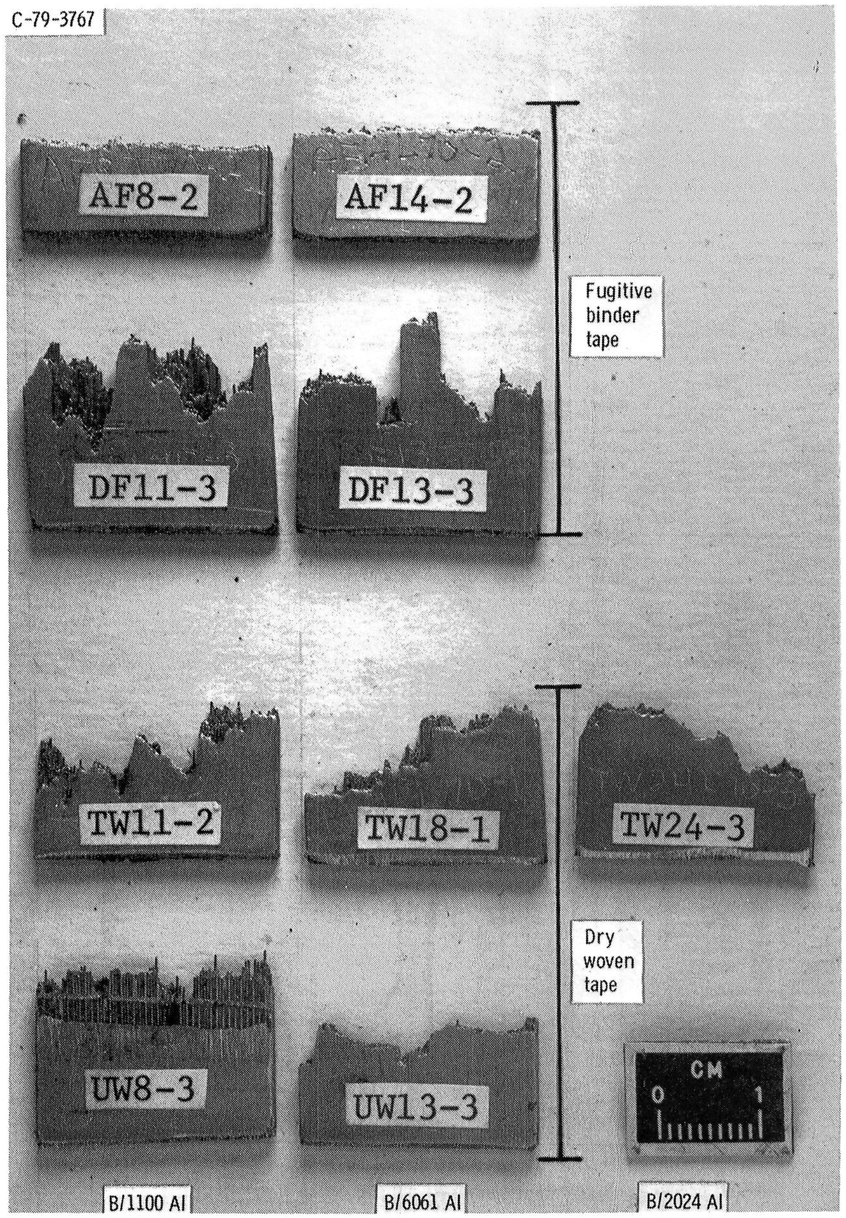
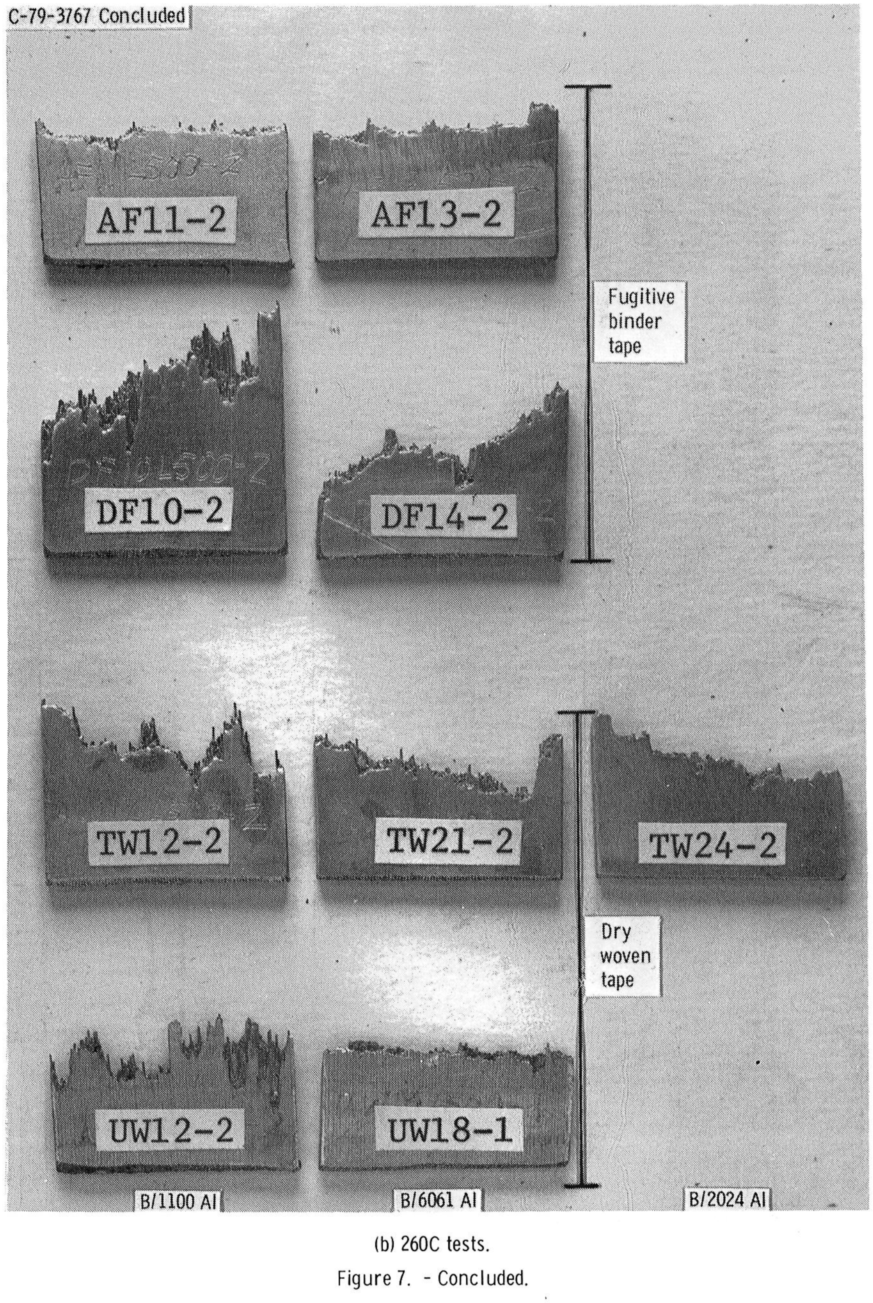


Figure 6. - Average longitudinal tensile strength of B/Al composites at 21C and 260C as related to fabricator and kind of tape.



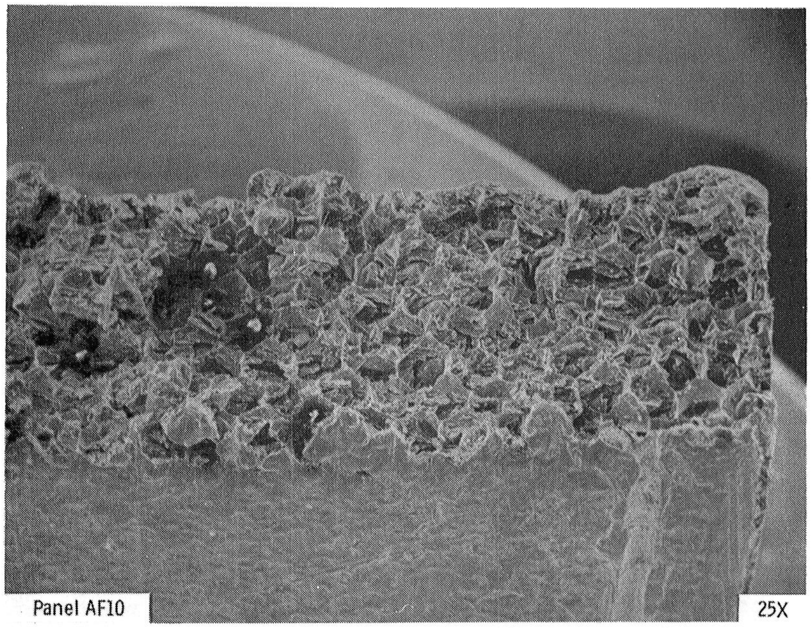
(a) Room temperature tests.

Figure 7. - Typical fracture areas of B/Al tensile specimens.

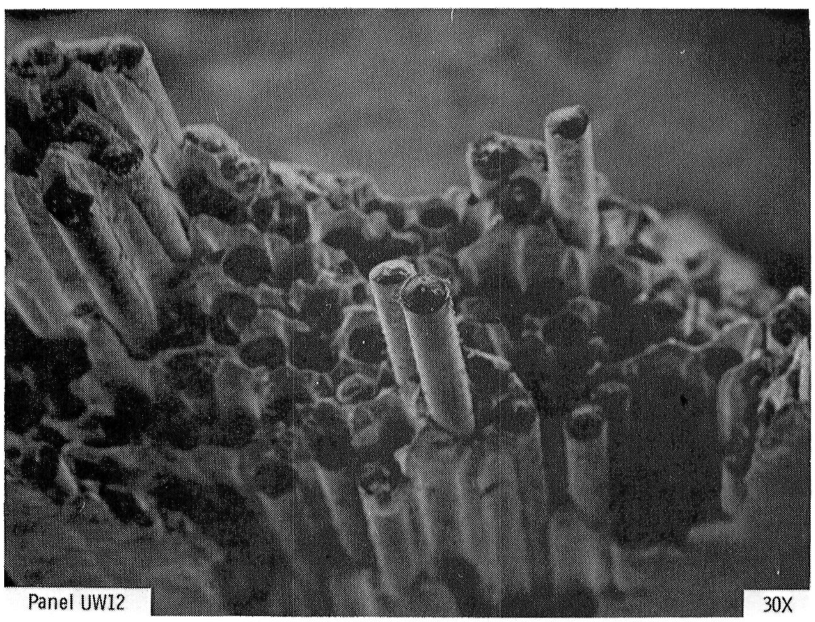


(b) 260C tests.

Figure 7. - Concluded.



(a) Even fracture with no delaminations or boron fiber pullout in 21^{0} C test.



(b) Boron fiber pullout in 260^{0} C test.

Figure 8. - Fracture surfaces of longitudinal B/Al tensile specimens.

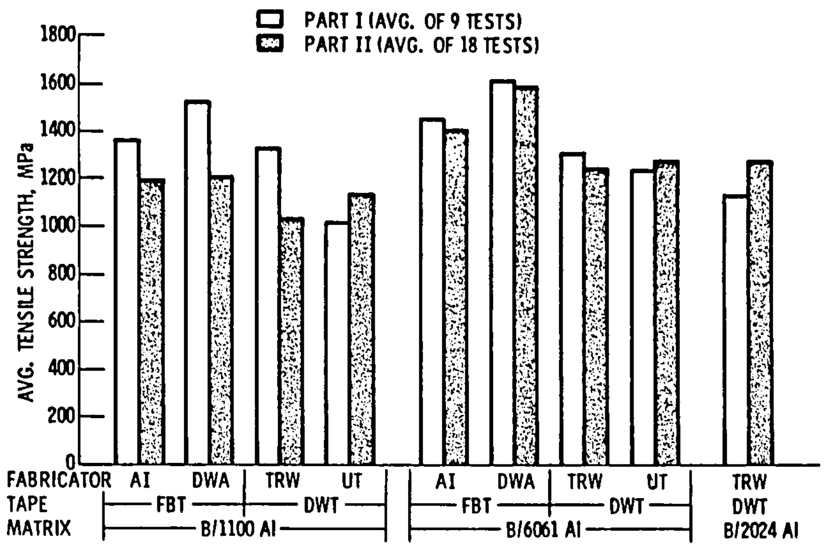


Figure 9. - Comparative average longitudinal tensile strength of B/Al composites at 21C for Part I and Part II of the program.

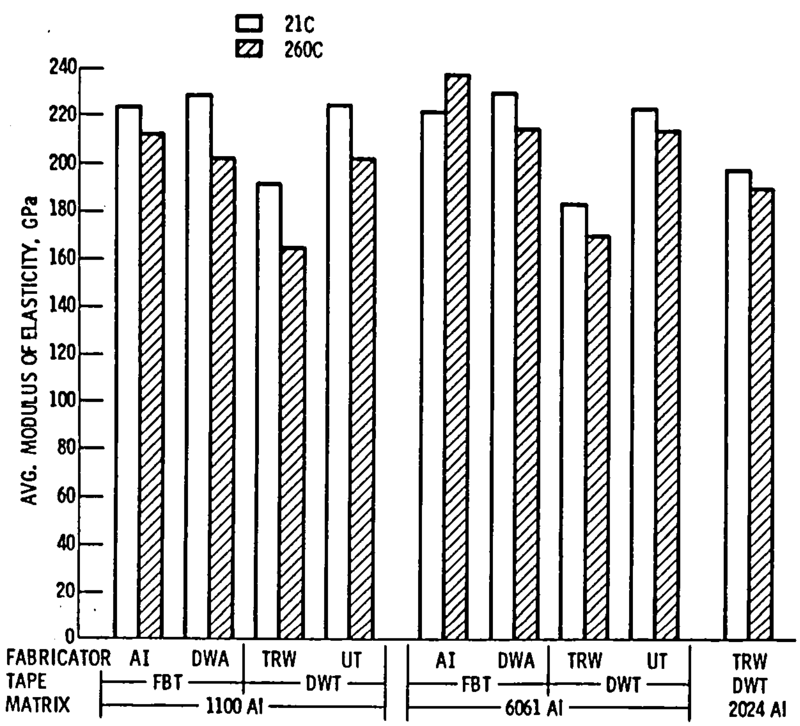


Figure 10. - Average longitudinal primary modulus of elasticity for B/Al composite panels at 21C and 260C.

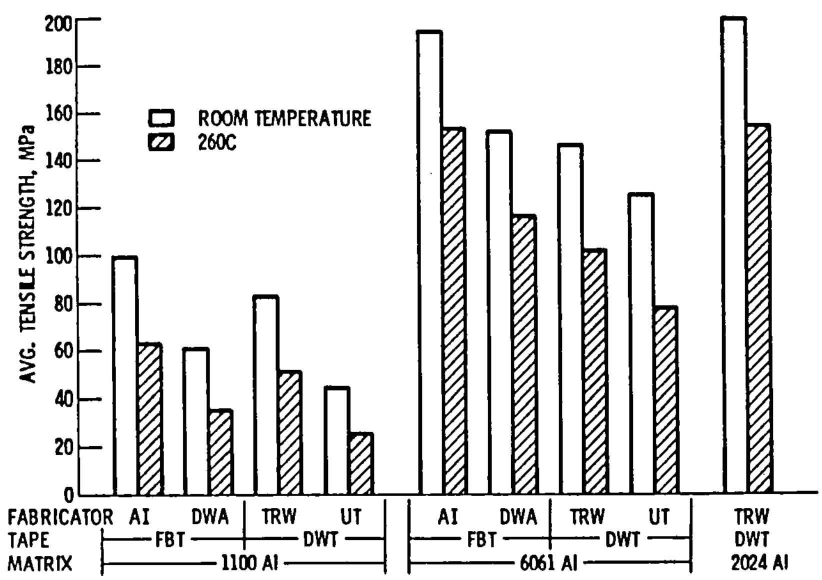
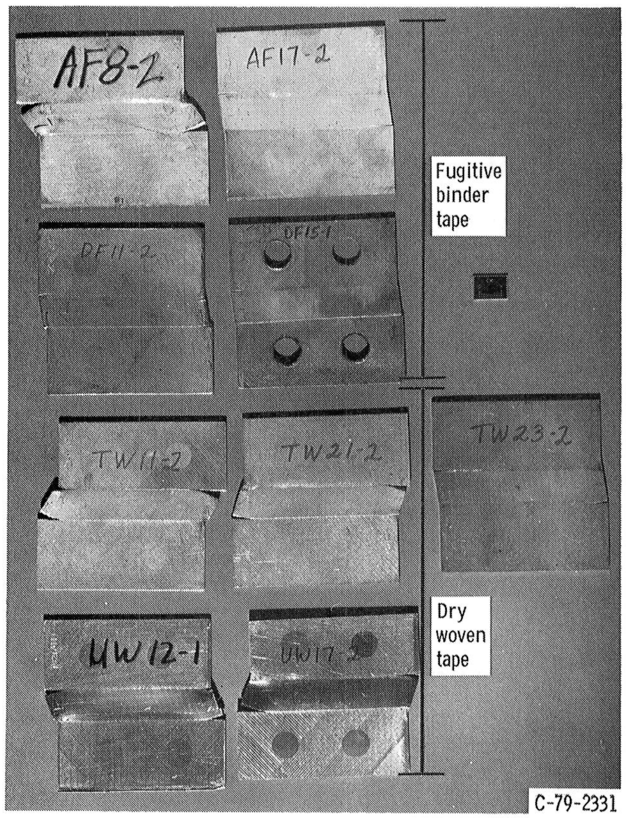


Figure 11. - Average transverse tensile strength of B/Al composite panels.



B/1100 Al B/6061 Al B/2024 Al

Figure 12. - Typical shear specimens tested at 21C.

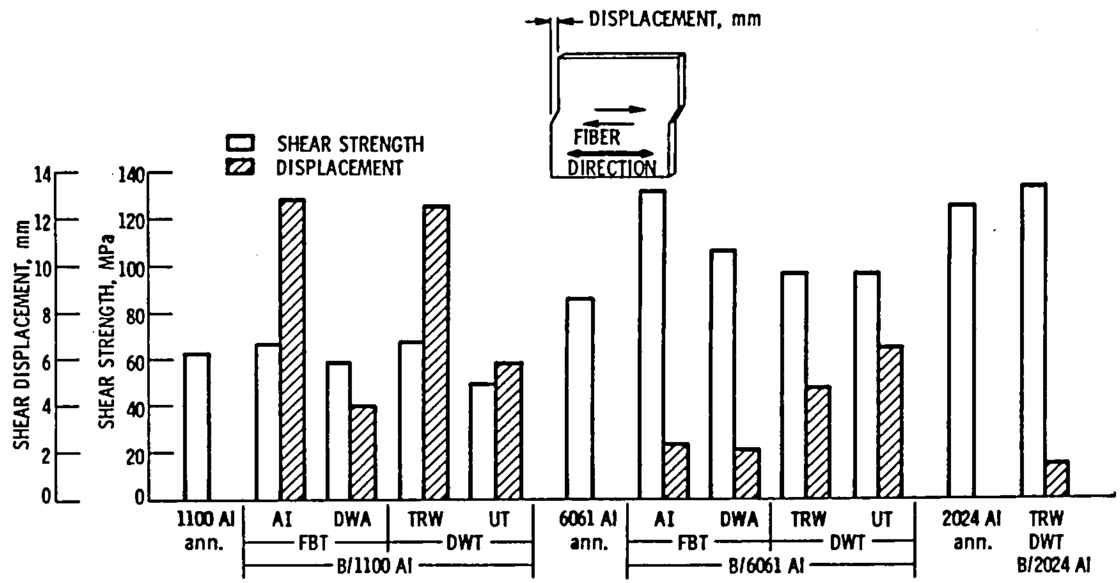


Figure 13. - Average shear strength and average displacement obtained from room temperature shear tests of B/Al composites.

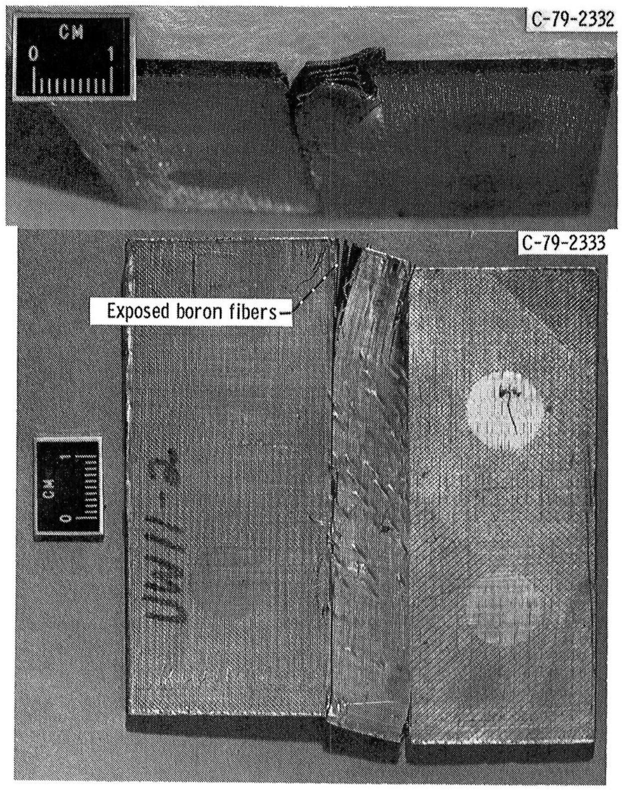


Figure 14. - B/1100 Al shear test specimen showing severe delaminations and separation of the boron fibers from the matrix.

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15. Supplementary Notes

16. Abstract

In Part II of a two-part program, four fabricators produced a total of 54 B/1100 Al, B/6061 Al, and B/2024 Al panels for evaluation. The 8-ply unidirectional, 45 to 50 volume percent, panels were made using 0.20-mm diameter boron fibers which were obtained from a single supplier. About half the panels were made using fugitive binder tape and the remainder from dry woven tape. Hot press consolidation was carried out in vacuum except for one set of dry woven tape panels which were hot pressed in air. A single testing contractor conducted nondestructive inspection, metallography, fractography and mechanical property tests. The mechanical property tests included 21° and 260° C tensile tests and 21° C shear tests. Panel quality, as measured by nondestructive evaluation, was generally good as were the 21° C tensile properties. The panels hot pressed in air, however, delaminated in the shear tests. Ultrasonic C-scan delineated these delaminated areas. Shear strength values were lower in these panels. But tensile strengths were not affected by the delaminations because of the relation between the tensile loading direction and the delaminations. Composite tensile strength was found to be proportional to the volume percent boron and the aluminum matrix rather than to the tape used or fabrication technique. Suitability of these composites for 260° C service was confirmed by tensile tests. Reproducibility of the tensile strengths of panels in Part II compared to those of Part I was very good for the B/6061 Al panels, fair for B/1100 Al and good for B/2024 Al panels. A recommendation is made to fabricate additional air hot pressed dry woven tape panels in order to more fully evaluate the most potentially cost-effective manufacturing process.

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