Mechanical Properties of Eutectic Bonded Boron Aluminum

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Results are presented of extensive testing recently completed on boron aluminum composites to determine mechanical property data for structural design and analysis. Test specimens were made from laminates fabricated using the eutectic bonding process, which requires low pressures (250-psi autoclave) and simple tooling. Average property data and associated test methods are given for unidirectional and cross-plied laminates at room temperature and 600°F. Mechanical fastener joint tests of laminates containing titanium interleaves are also presented. Results shows that the eutectic bonding process produces boron aluminum laminates with mechanical properties comparable to laminates produced by other fabrication processes. Compared to aluminum, which has approximately the same density, tests show that boron aluminum loaded in compression is 4½ times stronger and 3½ times stiffer. When loaded in tension it is twice as strong and three times as stiff.

Introduction

THIS paper gives the results of an extensive test program which determined the mechanical properties of boron aluminum composites fabricated by the eutectic bonding process. Property data were obtained as part of a contractual program with NASA Marshall Space Flight Center.[1] Test results show that the eutectic bonding process produces boron aluminum laminates with mechanical properties comparable to laminates produced by other fabrication processes, such as diffusion bonding. As a result of this program, complex, tapered laminates (skins) and shapes (stringers) of boron aluminum composites can be easily fabricated now with the low-pressure eutectic bonding process.

Fabrication requirements associated with boron aluminum have severely restricted the size and shape of boron aluminum structures. Complex shapes fabricated by the diffusion bonding process require high pressures (~5000 psi) and complex tooling (matching male-female dies); however, eutectic bonding developed by MDAC-E requires low pressure (250-psi autoclave) and simple tooling (male die only).

Eutectic bonding is a diffusion brazing process developed for fabricating boron aluminum components from composite monolayer. The monolayer foil consists of parallel and continuous 5.6-mil diameter boron filaments (40-45 % filament volume fraction) surrounded by a matrix of 1100 aluminum. This process relies on the diffusion of a thin surface film of copper into the aluminum matrix to form a liquid phase when heated above the copper-aluminum eutectic temperature of 1018°F.[2] The evolution of boron aluminum from its receipt as a monolayer foil into a laminated structural component involves several basic processing steps.[3] After monolayers are inspected and accepted, they are chemically cleaned to remove surface contamination. Each foil is then coated on both sides with a 20-microin, layer of copper by physical vapor deposition and laid up to the desired shape on a combination forming/bonding tool. Titanium interleaves follow the same basic processing steps as the boron aluminum monolayer; cleaning, coating, layup, and forming. The part is then covered with a steel sheet, which is welded directly to the tool to form an envelope which can be evacuated. Bonding is accomplished in an autoclave with the pack evacuated and under an external pressure of 250 psi while the temperature is raised to about 1040°F.

For uniaxial loading, advanced composite materials, such as boron aluminum, offer weight savings up to 50% over conventional materials. In addition, at elevated temperatures (300°-600°F) boron-aluminum structural efficiency is superior to resin matrix composites since resin critical properties degrade significantly with temperature. Specific compressive strength and modulus of elasticity of advanced composites are compared to conventional materials in Fig. 1. Properties are given parallel (0°) and perpendicular (90°) to filament direction. Resin matrix composite properties are from Refs. 4 and 5, boron aluminum properties are from MDAC-E tests as reported in this paper. It is interesting to note that specific compressive strength of boron aluminum and boron epoxy is higher than that of the other composites. In many structural applications, at least 50% of structure is designed for compressive loading; therefore, high compressive strength and buckling efficiency are very desirable.

A buckling efficiency comparison of composite and conventional materials is shown in Fig. 2. The orthotropic buckling equation for a simply supported plate loaded in uniaxial compression was obtained from Ref. 4. Predictions are based on lamina initial stiffness properties and laminates having sufficient thickness and ply stacking sequence repetition to be classified as homogeneous orthotropic materials. A 0°, ±45° laminate configuration was selected

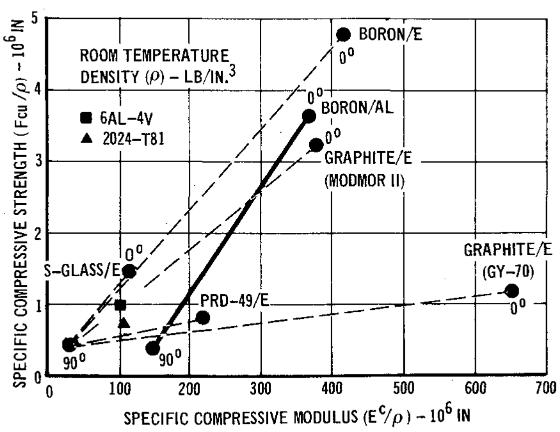

Fig. 1 Composite materials possess high structural efficiency in compression.

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for comparison of materials. The 0°lamina provide compressive strength and longitudinal stiffness while the ±45° lamina provide shear stiffness that is needed for high compressive buckling efficiency. Results of Fig. 2 show that cross-plying (±45°), required to develop buckling strengths for graphite-epoxy or boron-epoxy, is not necessary for boron-aluminum. Buckling strength of unidirectional (0°) boron-aluminum is very efficient due to its high transverse modulus ($E = 18$ msi) and shear modulus ($G = 8.5$ msi).

Test Results

Mechanical property test results given in this section for eutectic bonded boron aluminum agree with data from the *Advanced Composites Design Guide*[4] and show that it can be used at temperatures up to 600°F. Property data were obtained using test methods recommended for advanced composite laminates with individual specimens designed to insure the desired failure mode. Tensile tests were conducted with both straight-sided tensile coupons and sandwich beam specimens. Compressive tests were conducted with sandwich beam and edge-loaded sandwich panel specimens. In-plane shear tests were conducted on 0°, 90°, and ±45° laminates using the rail shear test method. A majority of specimens had valid failures in the gage regions, except longitudinal compression sandwich beam and edge-loaded panel specimens. These specimens sometimes experienced bondline and end brooming failures.

Unidirectional Laminates

Because strength and stiffness properties of boron aluminum laminates having any ply orientation are derived from the fundamental properties of the unidirectional laminate, tests of this laminate were conducted. Tensile, compressive, shear, and thermal expansion test data are summarized in Table 1. The unidirectional laminate has very high mechanical properties in the longitudinal (filament) direction and low to moderate properties in the transverse direction. Ultimate strength, strain, and initial values of tangent modulus and Poisson's ratio at both room temperature and 600°F are given. More than one test method was used in some cases to obtain property data, and the value shown was from the method judged to represent best the material and the ap-

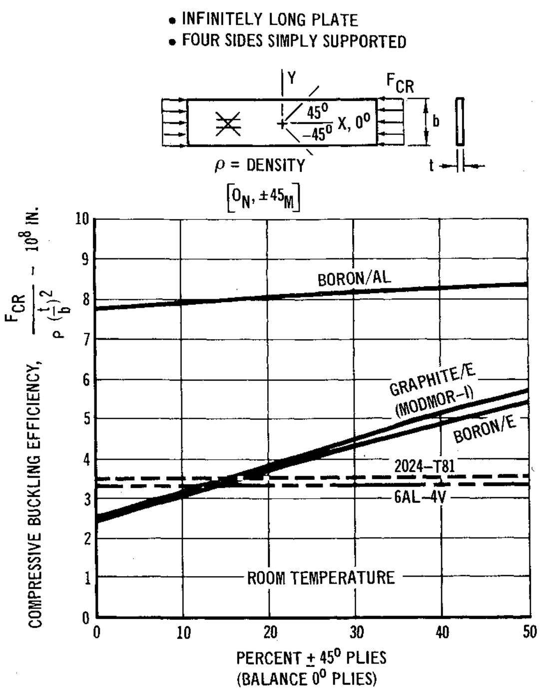

Fig. 2 Boron aluminum has high buckling efficiency.

Table 1 Average unidirectional boron aluminum mechanical property summary

PROPERTY	TEMP (°F)	ULTIMATE STRENGTH (KSI)	ULTIMATE STRAIN (μIN/IN)	INITIAL MODULUS (10^6 PSI)	INITIAL POISSON'S RATIO	TEST METHOD
LONGITUDINAL TENSION	R.T.	161	5740	30.0	0.25	COUPON
	600	155	6440	27.0	0.30	COUPON
LONGITUDINAL COMPRESSION	R.T.	343	10600	35.3	0.28	BEAM
	600	-	-	26.0	-	CRIPP.
TRANSVERSE TENSION	R.T.	14.7	3290	18.3	0.18	COUPON
	600	3.9	6480	11.7	0.095	COUPON
TRANSVERSE COMPRESSION	R.T.	37.5	24000	14.1	0.16	BEAM
	600	> 9.6	> 10700	15.9	0.17	BEAM
IN-PLANE SHEAR	R.T.	> 6.9	> 20000	8.5	-	RAIL SHEAR
	600	> 2.3	> 20000	4.0	-	RAIL SHEAR
INTERLAMINAR SHEAR	R.T.	10.1	-	-	-	SHORT BEAM
	600	3.1	-	-	-	SHORT BEAM

Notes:
(a) Density = 0.095 lb/in^3
(b) Average coefficient of thermal expansion (R.T. to 700°F):

Direction	α (10^{-6} in/in °F)
L	4.0
T	12.7

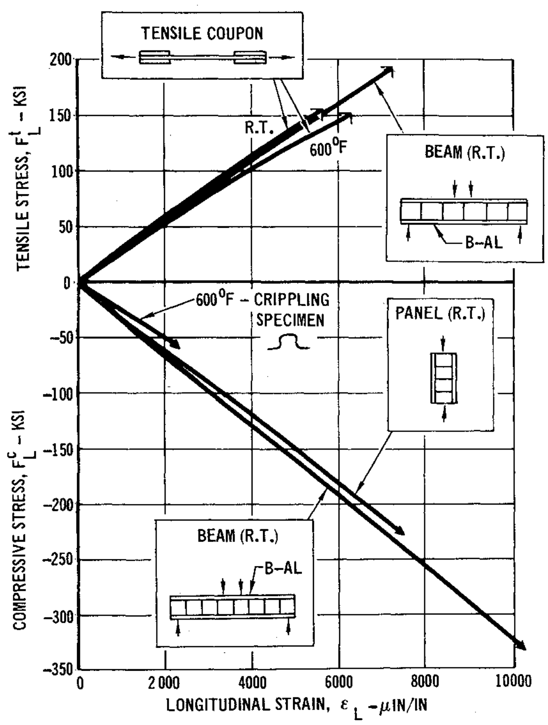

Fig. 3 Longitudinal tensile and compressive stress-strain response of boron aluminum.

plication. For example, longitudinal tensile coupon data were chosen over the higher sandwich beam data, since coupon properties are more representative of unsupported laminate applications such as skins and stringers.

Average longitudinal tensile stress-strain curves are shown in Fig. 3. Five tensile coupons and five sandwich beam specimens were tested at room temperature. Average strengths and stiffnesses obtained from coupon tests were 161 ksi and 30 msi, respectively, while similar properties obtained from beam tests were 194 ksi and 28.6 msi. All curves are essentially linear to failure. As expected, sandwich beam specimens produce a somewhat higher ultimate strength and a slightly lower modulus than the tensile coupons. Both of these changes are attributed to action of the core on composite facesheets. Five tensile coupons were also tested at 600°F with average strengths and stiffnesses of 155 ksi and 27 msi. These values reflect a 5% reduction in strength and 10% reduction in stiffness from room temperature coupon results.

The coupon configuration used for longitudinal tensile tests is shown in Fig. 4. It is 9 in. long and 1 in. wide with a 3-in. gage length. Each end tab has a 6-mil aluminum ply adhesively bonded to both sides of the specimen to prevent the serrated Instron jaws from penetrating the outer boron-aluminum ply and damaging the boron filament. Back-to-back strain gages were used to check for bending, even though the self aligning Instron grips used minimize bending of the specimen. Room temperature specimens were loaded to failure at a loading rate of 0.030 in./min. Elevated temperature specimens were soaked at 600°F for 30 min before being loaded to failure at a rate of 0.050 in./min. Continuous load-strain data were recorded for all specimens.

Sandwich beam specimen configuration used for the room temperature longitudinal tensile test is shown in Fig. 5. The beam is 22 in. long and 1 in. wide. Faceplates are adhesively bonded to an aluminum honeycomb core, which is 1.5 in. thick. In a 3-in. section at the center of the specimen, bonding is prevented by inserting Teflon tape between the core and tensile faceplate. This technique reduces the influence of the core on the faceplate and allows the faceplate to respond in a manner similar to a tensile coupon. The specimens were tested using a four-point load arrangement, as illustrated in Fig. 5. Loading rate on tensile specimen was 0.050 in./min. Continuous load-strain data were recorded for each specimen. No elevated temperature tests of sandwich beams were conducted, since adhesive bond failures at 600°F were anticipated.

Longitudinal compressive properties at room temperature were obtained for five sandwich beam and six edge-loaded sandwich panels. Average stress-strain curves for these specimens (shown in Fig. 3) are essentially linear to failure. Average ultimate strength and initial modulus obtained from longitudinal compressive beam tests were 343 ksi and 35.3 msi. Specimen configuration, instrumentaion, and test procedures used for longitudinal compressive beam tests were similar to those described earlier for the longitudinal tensile beam tests. Edge-loaded panels were planned for tests at 600°F because adhesive bond failures were anticipated if sandwich beams were used at this temperature. To evaluate the edge-loaded panel test method, six room temperature tests were conducted. Results from these tests indicated that the panel used was unacceptable because premature low failure strengths were obtained. Initial stiffness data from the panel are identical to sandwich beam data. The low failure strengths were caused by facesheet brooming at the ends of the specimen. Potting the specimen ends to prevent brooming was not successful. Consequently, longitudinal compressive tests of edge-loaded panels at 600°F were not attempted. Based on data from instrumented crippling specimen, however, the longitudinal compressive modulus at 600°F is estimated to be 26.0 msi.

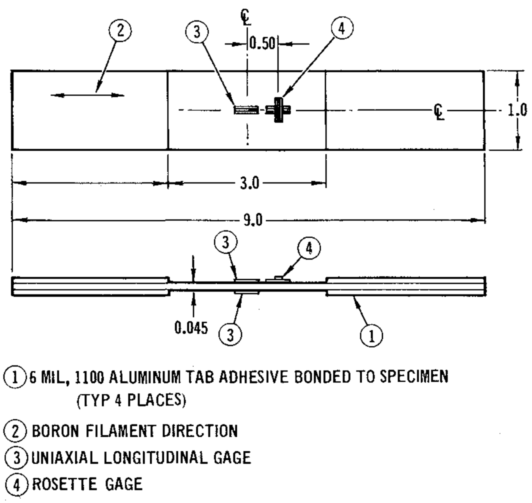

Fig. 4 Longitudinal tensile test coupon configuration.

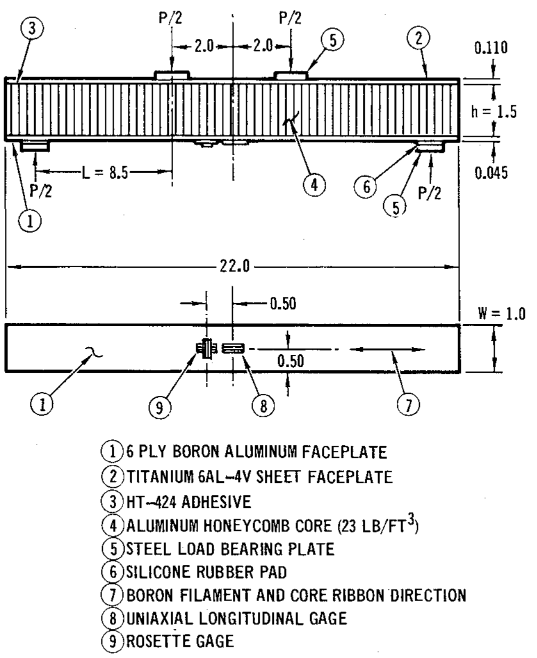

Fig. 5 Longitudinal tensile sandwich beam configuration.

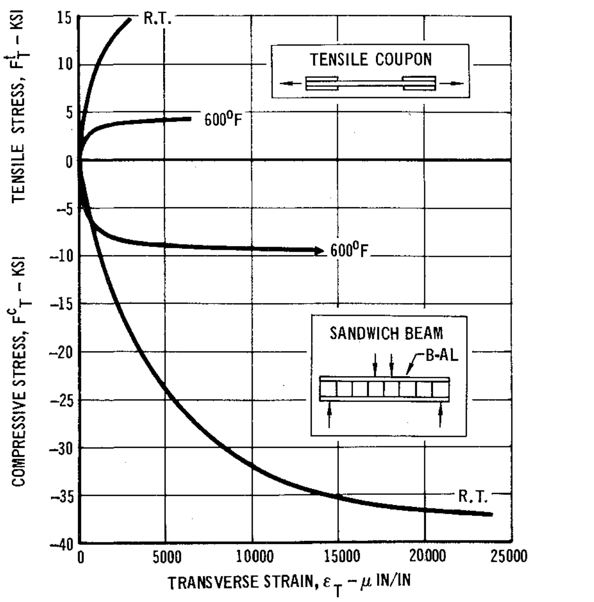

Fig. 6 Transverse tensile and compressive stress-strain response of boron aluminum.

Transverse tensile average stress-strain response obtained from five coupons tested at room temperature and five tested at 600°F is shown in Fig. 6. Since transverse properties are highly matrix dependent, nearly the entire stress-strain curve is nonlinear. Average transverse tensile ultimate strength, strain, and initial modulus at room temperature are 14.7 ksi, 3290 microin./in., and 18.3 msi, respectively. Average transverse tensile strength, strain, and initial modulus at 600°F are 3.9 ksi, 6480 microin./in., and 11.7 msi, respectively. Specimen configuration, instrumentation, and test procedures used for transverse tensile tests were similar to those described earlier for longitudinal tensile coupon tests.

Transverse compressive average stress-strain response from five sandwich beam specimens tested at room temperature and five tested at 600°F are shown in Fig. 6. Since transverse compressive properties are highly matrix dependent, nearly the entire stress-strain curve is nonlinear. Average transverse compressive ultimate strength, strain, and initial modulus at room temperature are 37.5 ksi, 24,000 microin./in., and 14.1 msi, respectively. At 600°F the average transverse compressive ultimate strength, strain, and initial modulus are 9.6 ksi, ≈ 10,000 microin./in., and 15.0 msi, respectively. The 600°F specimens had premature failure strains, which were probably due to adhesive bondline failures.

In-plane shear properties of unidirectional laminates were determined using the rail shear test method. To evaluate the rail shear test fixture, tests were initially conducted on 2024-T6 aluminum sheet, which has a known shear stiffness of 4.0 msi. Measured shear stiffness of 4.2 msi indicated the rail shear fixture was acceptable. Boron aluminum specimens with lengths of 8 in. and 12 in. were also tested to determine if length affected rail shear properties. Results showed that specimen length had little effect on either shear strength or stiffness, therefore, test results were not separated by specimen length. Boron aluminum specimens with filaments oriented both parallel (0°) and perpendicular (90°) to rails of fixture were tested. Typical stress-strain response curves at room temperature and 600°F are shown in Fig. 7. The differences in the 0° and 90° curves are within scatter of test data. Over the usable loading range of interest, up to 10,000 microin./in. shearing strain, strength, and stiffness properties obtained from the two specimen configurations are nearly the same. Average in-plane shear strength (at 10,000 microin./in.) and initial shear stiffness for either the 0° or 90° laminate at room temperature are 6.9 ksi and 8.5 msi. At 600°F, the average in-plane shear strength (at 10,000 microin./in.) and initial shear stiffness are 2.3 ksi and 4.0 msi.

The 0° and 90° rail shear specimens have considerably different failure modes. The 0° specimens (filaments parallel to rails) failed in matrix shear as a fracture plane parallel to the rails within the gage region. In addition, local transverse tensile failures were present at the narrow ends of specimens, due to loads required for equilibrium of the shear panel. These local end regions contain a complex stress state resulting in possible premature strength failures. Shear failure strains for the 0° specimens ranged from 15,000 to 20,000 microin./in.

The 90° specimens (filaments perpendicular to rails) had excessive shear strains at failure (~45° rotation of filaments). At large shear strains (> > 10,000 microin./in.) the filaments are carrying some of the shear in a way analogous to an incomplete tension field panel in metal structures. Consequently, the matrix is not in a state of pure shear in the monlinear region but is carrying a combination of shear and compression. For this reason shear strengths of 0° and 90° laminates are reported in Table 1 for shearing strains of 10,000 microin./in.

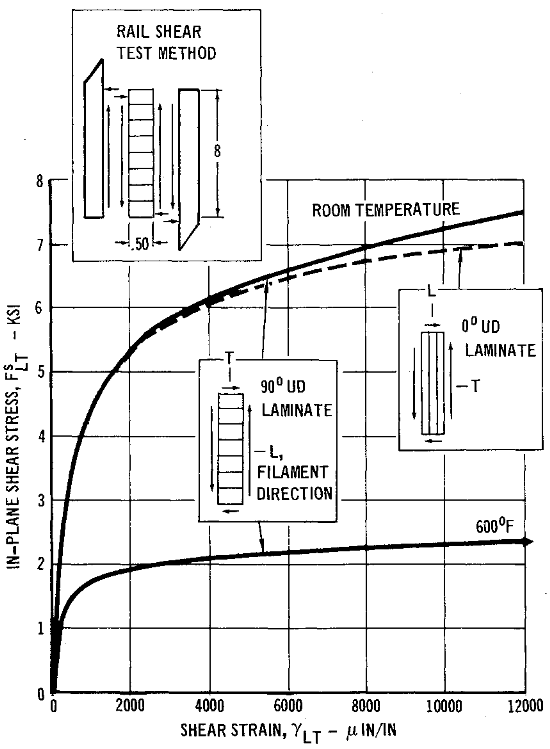

Fig. 7 Unidirectional boron aluminum in-plane shear stress-strain response.

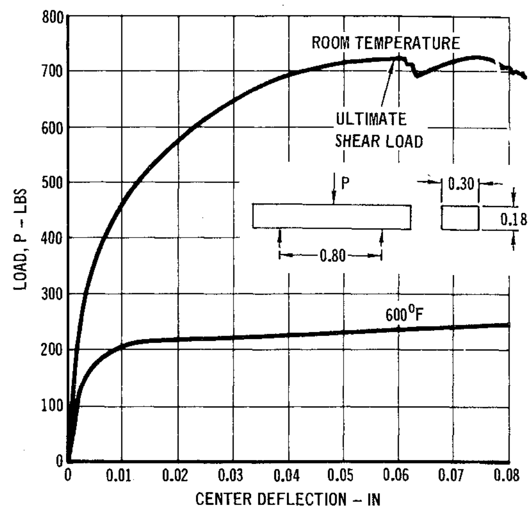

Fig. 8 Typical load-deflection response of boron aluminum interlaminar shear specimen.

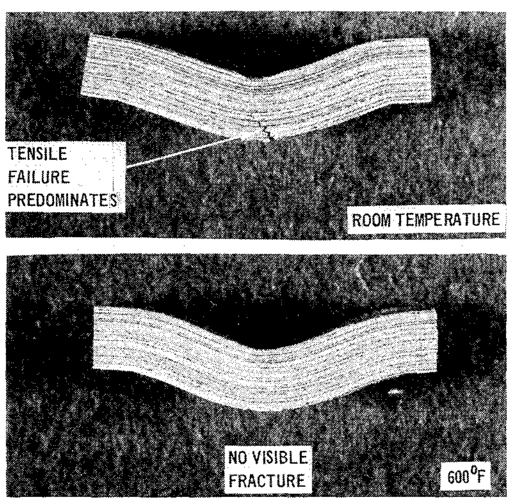

Fig. 9 Typical boron aluminum interlaminar shear specimen after test.

Interlaminar shear strength of unidirectional boron-aluminum was determined at room temperature and 600°F using the short beam shear test method. Each specimen was 1 in. long, 0.30 in.-wide, and 0.18 in. thick (24 plies). Average shear strength at ultimate load for the five room temperature specimens was 10.1 ksi and for the five specimens tested at 600°F after 30 min exposure was 3.1 ksi. Three-point loading was used to bend the specimen and cause interlaminar shear stresses. Typical load-deflection curves obtained at room temperature and 600°F are shown in Fig. 8. The nonlinear portion of the curve is due to shear yielding of the aluminum matrix, specimens tested at room temperature experienced predominantly tensile failures rather than shear failures, as shown in Fig. 9. The maximum load carried by these specimens was used to calculate shear strength at specimen failure. Specimens tested at 600°F experienced large deflections without failure, as shown in Fig. 9, therefore, shear strength was calculated at a load corresponding to the same deflection at failure as the room temperature test specimens (~0.06 in.).

Table 2 Average mechanical properties of ±45° boron aluminum laminates

PROPERTY	TEMP. (°F)	ULTIMATE STRENGTH (KSI)	ULTIMATE STRAIN (μIN/IN)	INITIAL MODULUS (10^6 PSI)	TEST METHOD
(tension, Y/X)	R.T.	26.2	27000	13.2	COUPON
	R.T.	34.5	17700	13.4	BEAM
COMPRESSION (Y/X)	R.T.	31.1	17200		BEAM
	600	8.7(a)	12500(a)	12.4	BEAM
SHEAR (Y/X)	R.T.	43.1	4200	12.5	RAIL SHEAR
	600	>21.9	>1500	9.9	RAIL SHEAR

Notes:
(a) Failure occured in core to faceplate adhesive bondline
(b) Average coefficient of thermal expansion (R.T. to 700°F):

$\alpha_x = \alpha_y = 5.65\ (10)^{-6}$ In./In./°F

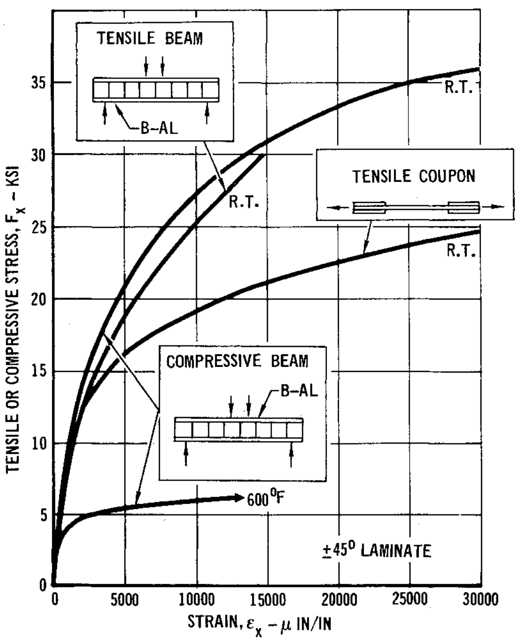

Fig. 10 Typical stress-strain response of ±45° boron aluminum laminate.

Cross-Plied (±45°) Laminates

Average tensile, compressive, shear, and thermal expansion test data for the ±45° laminate at room temperature and 600°F are summarized in Table 2. Uniaxial strength and stiffness values obtained from sandwich beam specimens are the average of five tests, while values shown for tensile coupons are the average of three tests. The ±45° laminate has the optimum ply orientation for shear strength (43 ksi at room temperature) and shear stiffness (12.4 msi).

Typical tensile and compressive stress-strain properties for the ±45° laminate are shown in Fig. 10. Because these curves are nonlinear over most of the range of interest, initial modulus values are applicable only to a small portion of the curve. A ±45° laminate loaded in either tension or compression experiences large deformations, due to shear forces acting on the matrix material. As a result, Poisson's ratio is large and continually changes, as shown in Fig. 11.

In-plane shear tests were conducted on the ±45° laminate at room temperature and 600°F using the rail shear test method. Stress-strain response for these conditions is shown in Fig. 12. Slipping of end tabs adhesively bonded to specimen in load introduction regions resulted in premature failures during 600°F tests. Therefore, shear failure strengths and strains are actually higher than values given in Table 2 and Fig. 12.

Mechanical Fastener Joints

Selective use of titanium interleaves and cross plies will significantly improve mechanical joint bearing strength of boron aluminum laminates, as shown in Fig. 13. For example, bearing strength of a 0° laminate containing 32% by thickness interleaves (150 ksi) is 170% greater than a 100% 0° layup (55 ksi). Also, the improvement in bearing strength

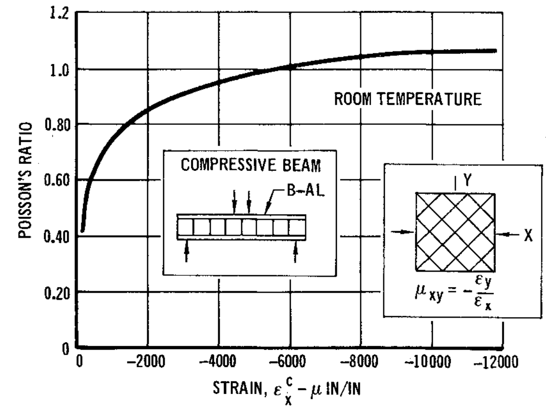

Fig. 11 Large Poisson's ratio for ±45° boron aluminum laminate.

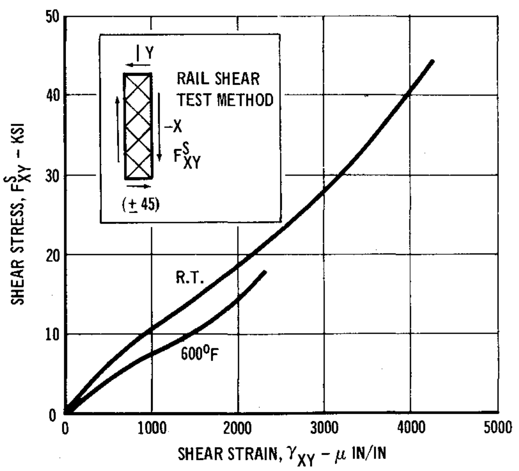

Fig. 12 Typical shear stress-strain response of ±45° boron aluminum laminate.

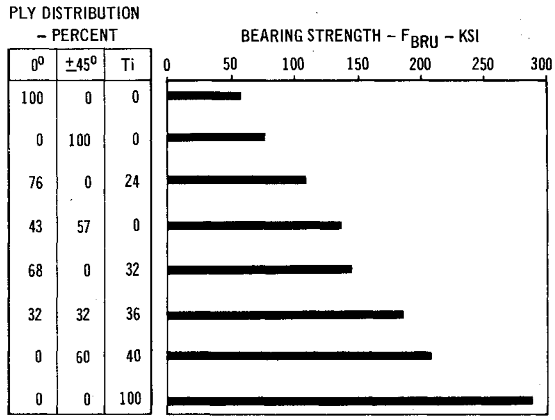

Fig. 13 Titanium interleaves and cross-plies improve boron aluminum bearing strength.

when 57% ±45° plies are added to a 0° layup (140 ksi) is 150% greater than an all 0° layup.

Data are based on test results of a specimen configuration having both a front-edge distance and side-edge distance to diameter ratio of 3. Specimens were tested with a 0.25-in.-diameter, high-strength bolt loaded in double shear and torqued to 60 in.-lb.

Applications

Complex, tapered, and contoured eutectic bonded boron-aluminum structures utilizing sophisticated reinforcement techniques have been successfully designed, fabricated, and tested to excess of design ultimate loads at temperatures up to 600°F.

An example of a complex boron aluminum structure fabricated using the eutectic bonding process is shown in Fig. 14. This 2-ft-long by 4-ft-wide skin-stringer panel was designed and successfully carried a load of 400,000 lb while at a temperature of 600°F. The load was introduced at the upper end of the centerline stringer and reacted as a distributed load on lower plane of the pane. This load exceeded design ultimate load by 15%. The panel contains unidirectional boron aluminum stringers selectively reinforced with titanium interleaves and tapered in thickness to satisfy the varying axial loads. The skin is a ±45° layup also containing titanium interleaves and is tapered in thickness to satisfy rapidly changing shear flows. A larger panel, 4 ft long by 6 ft wide, of the same configuration has been fabricated and delivered to NASA-MSFC for test. This panel (shown in Fig. 15) is designed to withstand a 350,000-lb concentrated load applied at one end and reacted by a uniformly distributed load at the opposite end while at a temperature of 600°F.

Conclusions

Mechanical property data and raw material quality have now stabilized to the point where rational and attractive design allowable data have been developed. The low-pressure eutectic bonding process developed by MDAC-E simplified fabrication of boron-aluminum structure by utilizing standard autoclave equipment and simple tooling. The test results presented show that the eutectic bonding process produces boron-aluminum laminates with mechanical properties comparable to laminates produced by other fabrication process. The low-pressure eutectic bonding process for fabrication of complex boron-aluminum structure has been successfully transformed from a laboratory operation to a production shop status. Appropriate process specifications have been developed to provide part quality assurance. In summary, sufficient technology and mechanical properties have been developed to permit application of boron aluminum to primary structure, such as Space Shuttle components, with high confidence.

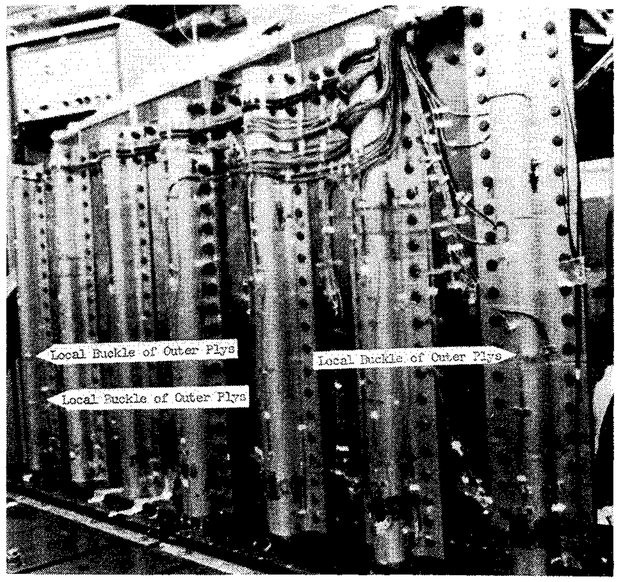

Fig. 14 Boron aluminum panel in testing machine.

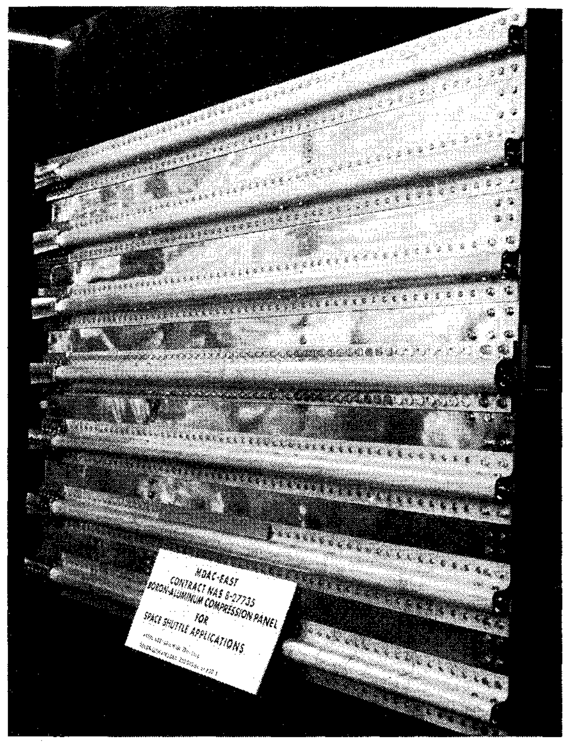

Fig. 15 Boron aluminum compression panel delivered to NASA-MSFC for test.

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