Eutectic Bonding of Boron-Aluminum Structural Components

Studies show that copper can be used as a eutectic former with aluminum to provide a reliable, low pressure method for fabricating boron-aluminum composites

PART I — EVALUATION OF CRITICAL PROCESSING PARAMETERS

BY J. T. NIEMANN AND R. A. GARRETT

ABSTRACT. This study was undertaken as part of a major program to develop a low pressure technique for fabricating boron-aluminum structural components. The method selected consists of joining monolayer foils together by a brazing process which relies on the diffusion of a thin surface layer of copper into the aluminum matrix to form a liquid phase when heated above the copper-aluminum eutectic temperature.

Laboratory investigations conducted to establish a suitable bonding cycle are described. First, the effect of holding time within a selected bonding temperature range on filament degradation was determined. Then, a copper coating thickness was selected to be compatible with a bonding cycle that would minimize the loss of filament strength. These studies showed that sound, strong joints could be produced by limiting the coating thickness to 20 microin. and restricting the bonding temperature to the range between 1030 F and 1060 F with the time not to exceed 15 min at the lower temperature limit or 7 min at the upper limit. Techniques for including titanium interleaves in boron-aluminum laminates are described and typical properties of eutectic bonded B/Al laminates are presented.

Introduction

During the past several years, the McDonnell Douglas Astronautics Co.-East has been evaluating metal-matrix composite systems for application to advanced spacecraft and missiles. These efforts have concentrated on the design, fabrication and testing of boron-aluminum structures. One of the first problems faced was selecting a joining method that could be used to produce structural components from monolayer foils of the composite. This led to the application of a brazing process that relies on the interdiffusion of dissimilar metals to form a liquid phase when heated above their eutectic temperature. This type of brazing has been used in a variety of specialized joining applications, (Refs. 1,2) and is known by various names such as eutectic brazing and diffusion brazing. Joining of boron-aluminum by the process described in this paper depends on the diffusion of a thin surface layer of copper into the aluminum matrix to form a eutectic liquid when heated above 1018 F.* This particular development has been termed eutectic bonding.

Several steps were involved in the evolution of eutectic bonding from a laboratory development to a production process. The more critical processing parameters were examined first to establish a bonding thermal cycle and to define copper thickness requirements. Then, production processing methods for chemical cleaning, copper coating, bonding, machining and joining were evaluated and selected. When this was accomplished, mechanical property tests were conducted to establish design allowables. Finally, large, complex structural components were designed, fabricated and tested. Major investigations conducted during this period will be discussed in this paper. Part I will describe the metallurgical studies conducted to select a thermal cycle and copper coating thickness for joining boron-aluminum to itself and to titanium and will present typical mechanical properties. Part II will be concerned with process development and component fabrication.

The authors are associated with McDonnell Douglas Astronautics Co. - East, St. Louis, Mo. J. T. NIEMANN is Senior Group Engineer, Materials and Processes Dept. R. A. GARRETT is Program Manager, Advanced Composites Programs.

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**All units are presented in the English system; factors for converting to the International System are presented in Table 1.*

Selection of a Joining Process

The high strength, high elastic modulus and low density of boron-aluminum make it an attractive candidate material for weight-critical aerospace structures. It is much superior to conventional materials from the standpoint of specific strength and specific modulus. For example, boron-aluminum with the boron filaments oriented longitudinally combines the strength and stiffness of high strength steel with the density of aluminum. A less desirable feature is its high degree of anisotropy. In the transverse direction, the mechanical properties are determined by the aluminum matrix and consequently they are much lower than the longitudinal properties which are determined by the very high strength boron filaments.

Because of the potential offered by boron-aluminum, there has been a concerted effort to develop methods of fabricating structural components from this material. The objective of these studies has been to utilize the good longitudinal mechanical properties of the composite while compensating for the low transverse properties through techniques such as cross-plying and adding local reinforcement.

Two general approaches have been followed to achieve this objective. Diffusion welding was developed first and proved to be an economical method of producing flat plates and sheets and simple structural shapes which could be formed after consolidation by the diffusion process. The major drawback to this process is its limited versatility. Greater design flexibility is offered by a second technique in which laminated structures are built up from monolayer foils of the composite. These individual foils are first formed to the desired shape and then bonded together. This approach facilitates cross-plying, adding local reinforcement through interleaving with another material and varying the thickness of detail parts for maximum weight savings. A typical laminated structure incorporating these features is shown in Figure 1.

In order to apply the built-up laminate approach, a method of joining individual foils together had to be selected. Brazing appeared to be an ideal choice when combined with vacuum bagging and an externally applied hydrostatic pressure to provide intimate contact between adjacent monolayers and conformance to the desired shape. However, the conventional silicon-containing aluminum base brazing filler metals require heating to temperatures in excess of 1080 F. Even very short time exposures at this temperature result in a fiber-matrix interaction which drastically lowers composite strength. This interaction can be minimized by using boron filaments which have been coated with silicon carbide, but this solution is accompanied by increased cost and lower mechanical properties. To avoid these penalties, a study was undertaken to develop a lower temperature joining process.

The need for a lower temperature brazing process led to the investigation of eutectic bonding as a possible method of fabricating B/Al structures. Although many elements form eutectics with aluminum, copper was selected as the most promising for B/Al fabrication because of its low cost, availability and ease of deposition by electroplating and physical vapor deposition. Furthermore, it is a common element in aluminum alloys and did not present compatibility problems with the 1100 aluminum matrix. In fact, substantial solid-solution strengthening of the matrix by the copper addition was anticipated.

Mechanics of Eutectic Bonding

The eutectic bonding process resembles brazing in that joining is effected through a liquid phase which forms at a temperature below the melting points of the base metals involved. The major difference lies in the manner in which the liquid is formed. Brazing utilizes a low-melting filler metal while eutectic bonding relies on the diffusion of copper into the aluminum matrix to form a liquid at the joint interface when heated above the aluminum-

Table 1 — Conversion Factors for International System of Units[a]

To convert from	To	Multiply by
Farenheit	kelvin	K = 5/9 (F + 459.67)
inch	meter	$2.54(10)^{-2}$
pound/inch³	kilogram/meter³	$2.76799(10)^{4}$
pound/inch²	newton/meter²	$6.89476(10)^{3}$
torr	newton/meter	$1.3332(10)^{2}$

(a) From Ref. 3

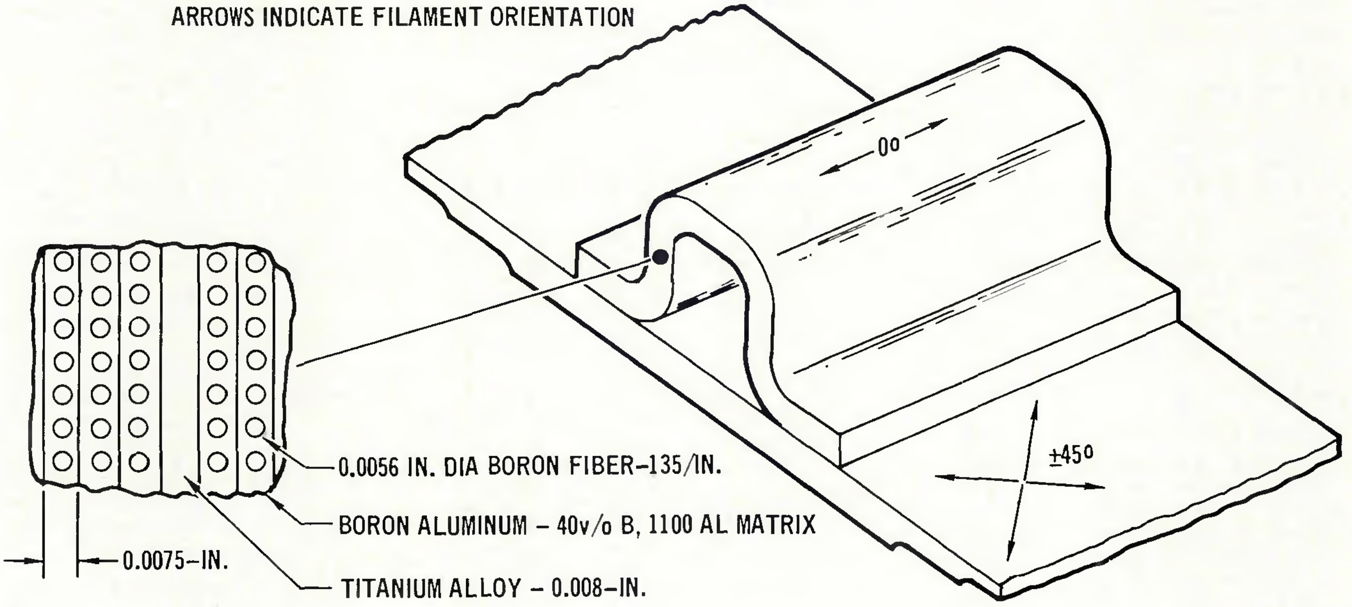


Fig. 1 — Typical structural application for boron-aluminum

copper eutectic temperature of 1018 F.

The metallurgical reactions which lead to the formation of a liquid phase and determine the final microstructure can be described in terms of Al-Cu phase relationships and diffusion theory. Basically, these two metals will interdiffuse when heated while in close contact, and a concentration gradient varying from 100% Al to 100% Cu will exist across their interface.

The metallurgical structure within this gradient will be determined by the temperature and phase equilibrium relationships (Fig. 2). Below the 1018 F eutectic temperature, the Al-Cu system contains two primary solid solutions and a number of intermediate phases. Heating within this temperature range will result in the formation of the two solid solutions and between them distinct bands of each intermediate phase. The width of these bands will be determined by the time at temperature and relative diffusivities of the two metals. Near the eutectic temperature the diffusivity of copper in nearly pure aluminum is about 2000 times greater than that of aluminum in nearly pure copper (Ref. 5). Therefore, the direction of diffusion will be predominantly from the copper into the aluminum. As a result, the aluminum-rich solid solution zone will be much wider than the copper-rich zone.

A eutectic liquid results from the interdiffusion of aluminum and copper and the resulting formation of the aluminum-rich solid solution. Therefore, the mechanics of eutectic bonding, described below, are based on the formation of this solid solution; existence of the other phases is disregarded.

As shown in Fig. 3, the process begins with the copper-coated composite monolayer foils sandwiched together (the copper content of the 1100 aluminum matrix is essentially zero). As the monolayers are heated, diffusion begins. At any time in the heating cycle, the amount of copper in solid solution will vary from a maximum near the original interface to zero a short distance away. The depth of diffusion is determined by the rate of heating and temperature while the copper content of the solid solution is determined by the solid solubility limit of copper in aluminum. This limit varies with temperature, ranging from less than 0.5% at room temperature to a maximum of 5.65% at 1018 F. During the heating stage, the concentration of Cu in solid solution is determined by the instantaneous temperature and associated solubility limit while the depth of copper penetration continually increases with time.

When the temperature reaches 1018 F, melting begins in the aluminum which contains 5.65% Cu. The first liquid formed at 1018 F is the eutectic composition, Al-33.2% Cu. Further heating to the bonding temperature, nominally 1050 F, produces additional melting in the aluminum-rich solid solution to a depth where the copper content is equal to about 4% — the solid solubility limit at the nominal 1050 F bonding temperature. Normally at this temperature, the liquid phase of an Al-4% Cu alloy would contain about 25% Cu. However, the liquid can contain about 40% Cu so any remaining copper coating is dissolved in the unsat-

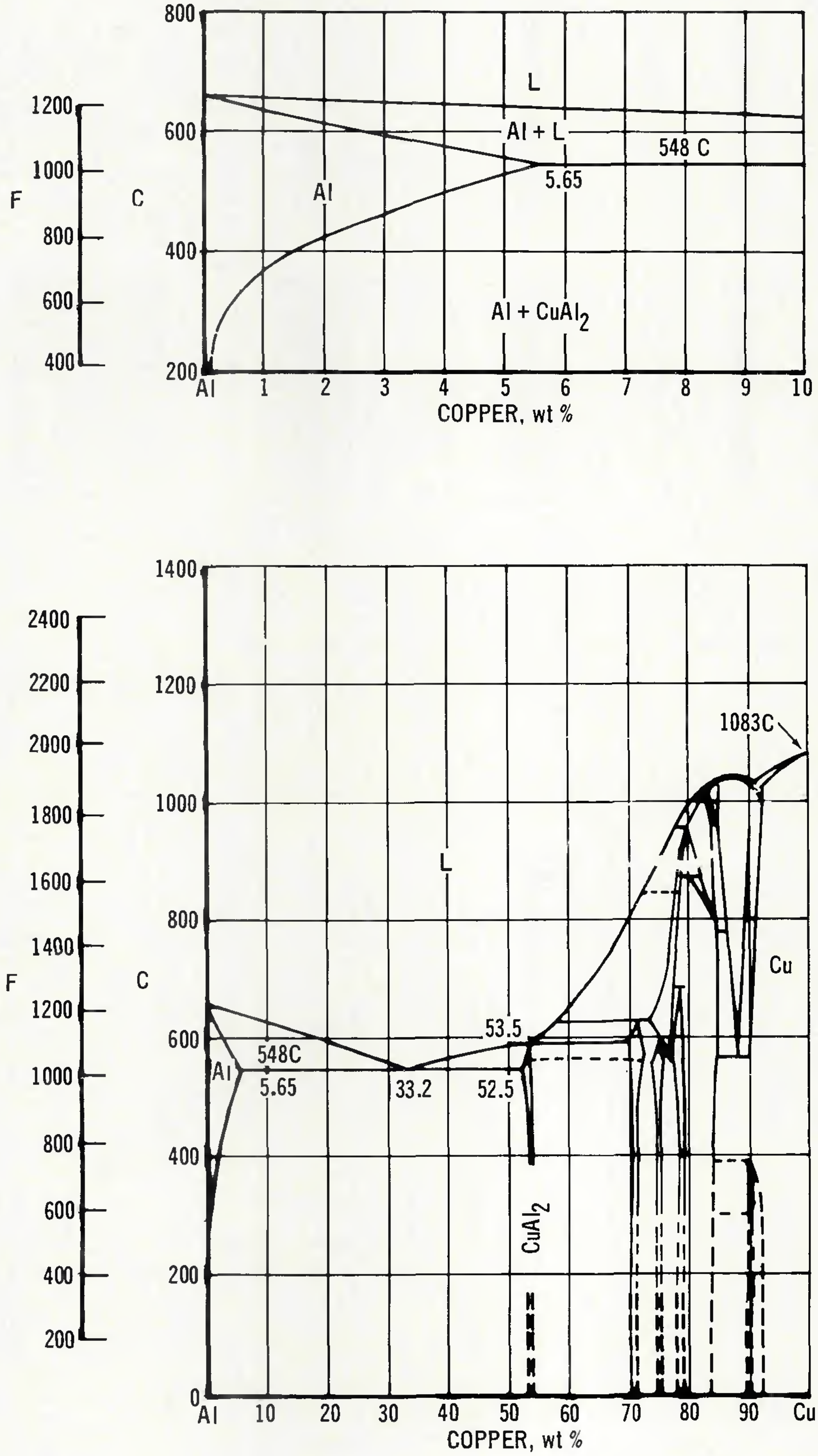


Fig. 2 — Aluminum-copper phase diagram

urated liquid or depleted through the continuation of the diffusion-melting process.

The metallurgical reactions which occur during solidification determine the microstructure and properties of the joint and are dependent upon the time the assembly is held above the eutectic temperature. During this time, copper continues to diffuse into the matrix so that the copper content of the liquid is continually decreasing. When the process is applied to boron-aluminum, the time is sufficiently long so that all the liquid is depleted and solidification occurs isothermally at the bonding temperature. Upon cooling, the final microstructure will consist of fine particles of $CuAl_2$ intermetallic compound randomly distributed in an aluminum matrix containing a small amount of copper in solid solution. These particles are precipitated from a solid solution as the temperature decreases and the solubility limit is exceeded. As shown in Fig. 3, the final copper distribution will vary on a microscale from a maximim value of less than 5.65% at the original interface to a minimum value some distance away.

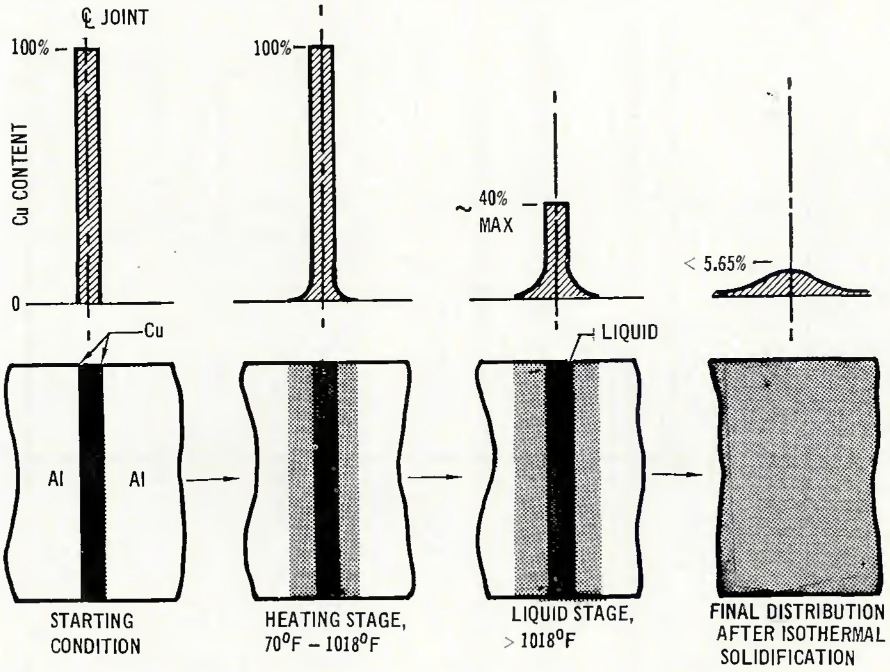


Fig. 3 — Variation in copper concentration and distribution during eutectic bonding

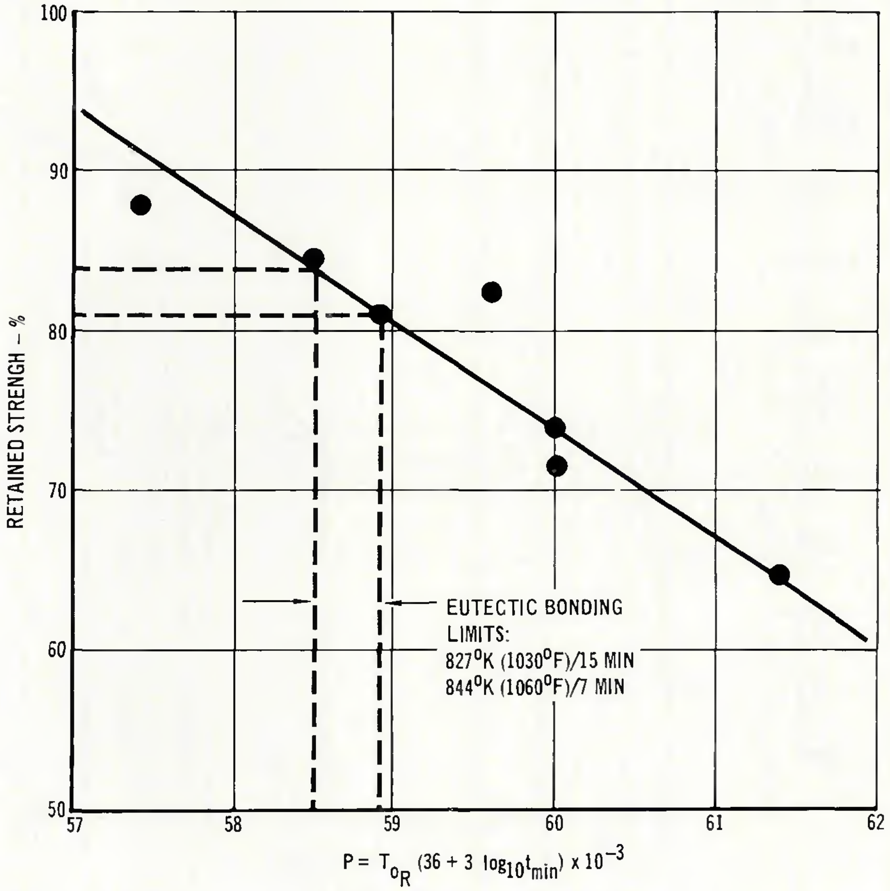


Fig. 4 — Effect of elevated temperature exposure on strength of boron-aluminum monolayer foil

A less desirable microstructure can be formed if the joint is cooled prematurely and the liquid undergoes the eutectic decomposition to form a solid solution and the intermetallic compound. Then, the solid solution will blend into the previously solidified material. This will leave the intermetallic compound isolated at the joint centerline either as isolated particles distributed along the interface or, under the most extreme conditions, as a continuous (or near continuous) stringer along the bond line. This condition is avoided during eutectic bonding by carefully balancing the copper thickness and time/temperature profile to ensure isothermal solidification.

Definition of Bonding Cycle Parameters

Metallurgical reactions associated with eutectic bonding suggested the most critical features of the process were related to the thermal cycle and the copper thickness. It was apparent that successful bonding of boron-aluminum would require careful balancing of these two variables to provide high strength joints free of brittle intermetallic compound networks through complete diffusion of all the copper coating. At the same time, extended high temperature exposure that would result in excessive fiber degradation had to be avoided. Two studies were undertaken to achieve this balance. The first was made to establish the effects of time-temperature exposures likely to be encountered in eutectic bonding on filament strength. Based on these results, limits were established for production control of bonding parameters and a second study then made to establish compatible coating thickness limits.

Bonding Cycle Study No. 1 — Fiber Degradation

It has been well documented that high temperature exposure of B/Al composite can result in lowered strength properties and that the magnitude of the loss is directly proportional to both time and temperature. Generally, degradation has been attributed to the formation of the compound AlB_2. Reaction zones at the fiber/matrix interfaces have been observed at 5000X magnification on samples subjected to severe exposure conditions such as 1000 F for 500 h. However, measurable strength degradation will occur at 1000 F in as short a time as one hour (Refs. 6,7).

Although the problem of fiber degradation has been studied by several investigators, their test results were not directly applicable to the eutectic process. Time/temperature conditions were not comparable nor were data available on the effect of the copper added to the matrix through diffusion. Therefore, a two part study was undertaken to determine the effect of eutectic bonding on fiber/matrix interaction. First, the effects of thermal exposures which simulated eutectic bonding on composite strength were evaluated. Then, tests were conducted to determine if copper influenced the reaction between boron and aluminum.

The first series of tests was made on uncoated samples cut from a single monolayer foil. This foil was cut into seven strips, 1-1/8 in. wide × 21 in. long. Five specimens from each group of nine were degreased, thermally exposed and tested. The remainder were tested in the as-received condition to establish baseline properties. This procedure was followed to minimize data scatter, which normally is high in composite materials, by ensuring that all specimens within a group shared common filaments.

Samples were heated in a vacuum furnace at times and temperatures ranging from 1020 F for 7 min to 1160 F for 7 min. The specimens were heated to the desired temperature at a rate of 20 F per min, and held for a predetermined time under a vacuum of approximately 1×10^{-5}torr. After the exposure time had elapsed, the specimens were fast cooled to 900 F by back-filling the furnace with argon, and then allowed to slow cool to 250 F before removal from the furnace.

Both the exposed and unexposed specimens were tensile tested to failure at room temperature using a cross-head travel rate of 0.05 in./min. Pneumatically tightened grips, which contained linings of hard rubber, were used to minimize specimen damage. Also, the specimens were aligned carefully to avoid introducing bending stresses.

The tensile test results were expressed both as monolayer strength and filament bundle strength. The latter value is derived by assuming that the matrix contribution to longitudinal strength is not significant from the following expression:

$$\sigma_B = \frac{F}{A_f W C_f}$$

where

σ_B = filament bundle strength
F = failing load of coupon
A_f = cross-sectional area of a single filament
W = width of coupon
C_f = filament count (number of filaments per unit width of composite)

Bundle strength is often the preferred method for evaluating monolayer and laminate test results because it eliminates specimen-to-specimen variation in filament volume content and inaccurate thickness measurements of the thin monolayer attributable to surface irregularities. In this study, the fibers in each specimen were measured over a 1-in. width to obtain an accurate filament count and calculation of bundle strength.

Analysis of the tensile test results listed in Table 2 showed that boron fiber degradation occurred throughout the time/temperature range evaluated; the degree of degradation was governed by the severity of the exposure. For example, at 1060 F a holding period of 7 min resulted in a strength loss of about 15%; extending the holding time to 30 min increased the loss to 35%. A similar effect occurred when the temperature was increased. Holding at 1030 F for 7 min resulted in a 12% strength loss while exposure to 1100 F for the same amount of time produced a 29% loss.

The final fiber degradation tests were made to determine if the copper added to the 1100 aluminum alloy matrix as a result of eutectic bonding would influence fiber/matrix interaction. In these tests, copper coated and uncoated B/Al samples were exposed simultaneously to selected thermal cycles, tensile tested, and compared with as-received specimen results. The previously described procedures for sampling and testing were followed.

A total of 30 coated and 30 uncoated samples was thermally cycled and tested. One half of each type were held at 1060 F for 15 min which represented an extreme condition and the others at 1030 F for 15 min to represent a eutectic bonding cycle. These tests showed about 5% increase in the amount of degradation measured in coated samples held at 1060 F for 15 min. An increase of only 2% was noted for the simulated eutectic bonding cycle at 1030 F; this amount was considered tolerable.

To better define fiber degradation in terms of time-temperature relationships, the filament bundle strength data reported in Table 2 were expressed in terms of a Larson-Miller parameter. This representation is shown in Fig 4. Then maximum and minimum conditions were selected for eutectic bonding based on anticipated production limitations. It was

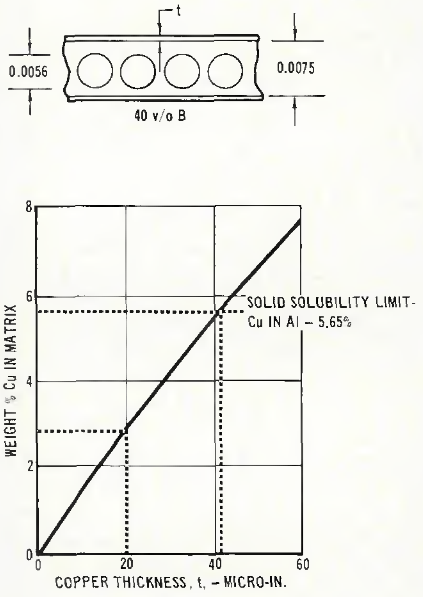
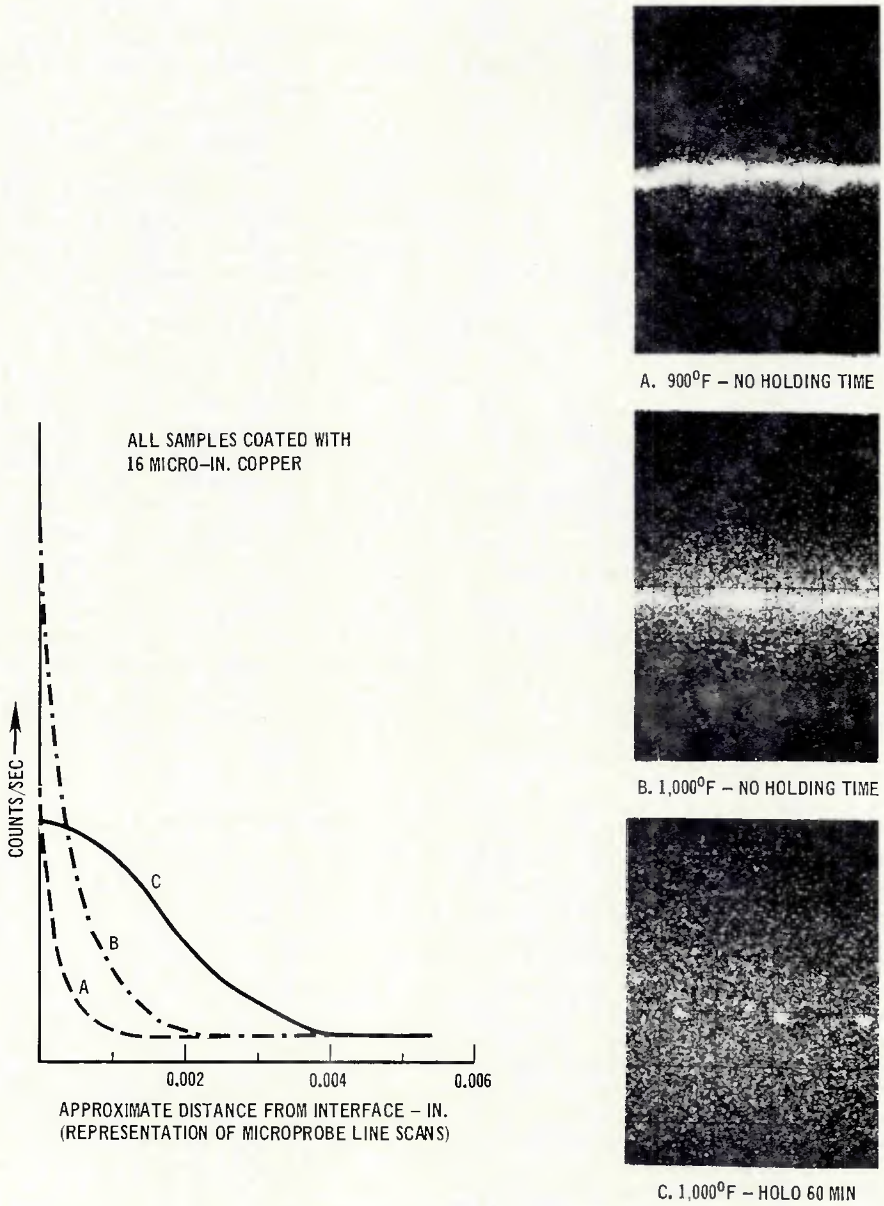


Fig. 5 — Relationship between coating thickness and copper content of matrix

Table 2 — Room Temperature Longitudinal Tensile Strength of Thermally Exposed and Unexposed Boron-Aluminum

Exposure condition	Average monolayer ultimate strength, ksi	Average filament bundle strength, ksi	Degradation, %
Unexposed controls	185	441	—
1020 F-30 min	150	364	17.6
1030 F-7 min	167	389	11.9
1030 F-15 min	159	358	19.0
1060 F-7 min	157	374	15.5
1060 F-15 min	133	317	28.3
1060 F-35 min	123	289	34.6
1100 F-7 min	135	316	28.6



A. 900°F – NO HOLDING TIME

B. 1,000°F – NO HOLDING TIME

C. 1,000°F – HOLD 60 MIN

Fig. 6 — Effect of time and temperature on diffusion of copper coating during eutectic bonding heating cycle

assumed that bonding conditions might range from 15 min at 1030 F to 7 min at 1060 F. With these extremes, it was predicted that eutectic bonding could result in a maximum strength loss ranging from about 16% to 19%. While this amount was considered appreciable, it was still well below the 35% or more that would occur in a brazing operation which normally requires heating near 1100 F.

Bonding Cycle Study No. 2 — Copper Coating Thickness

The thickness of the copper coating applied to boron-aluminum monolayer was selected to accomplish the following objectives:

(a) complete consumption of the copper layer.

(b) isothermal solidification at the bonding temperature to avoid both eutectic decomposition and concentration of $CuAl_2$ along the bond line.

(c) total amount of copper available for dispersion through the aluminum matrix must not exceed the maximum solid solubility of copper in aluminum, (5.6%), to ensure (a) and (b) above.

These goals could be accomplished only by using very thin copper coatings.

Figure 5 shows the relationship between coating thickness and matrix copper content. The upper limit for coating thickness, assuming no loss of liquid during bonding, is about 42 microin. to stay within the solubility limit. A coating thickness of 20 microin. per side was selected as a target maximum value to further minimize coating thickness and thereby ensure that the other objectives would be met.

Before proceeding with eutectic bonding using 20 microin. thick copper coatings, an analysis was made to determine if enough of the coating would survive the diffusion process during heating to provide a liquid phase. For this purpose it was again assumed that the aluminum-rich solution region was of prime importance and that all the copper which crossed the interface went into solid solution. This total amount was defined by the expression:

$$x\rho_c = 1.1284\sqrt{Dt}\quad (C_s - C_o) \quad \text{(Ref. 5)}$$

where x = thickness of coating lost through diffusion, cm.

ρ_c = density of copper = .324 lb/in^3

D = diffusion coefficient of Cu in Al, cm^2/sec.

t = time, sec.

C_s = copper concentration maintained at surface; for this analysis $C_s = C\rho_a$ where C is solid solubility limit of Cu in Al and ρ_a is density of alloy, ~.1 lb/in^3

C_o = initial copper concentration in Al = 0

Substituting and changing units to have t in hours and x in inches:

$$x = 8.25\,C\sqrt{Dt}$$

The factors that determine the rate of coating loss are the diffusion coefficient, time, and solid solubility limit of Cu in Al. Both the diffusion coefficient and solid solubility increase with temperature. Because of the interrelationships the rate of coating loss during heating at a uniform rate cannot be calculated readily. However, the derived expression was used to calculate the rate of diffusion under constant temperature conditions. Temperatures near the eutectic bonding temperature were considered because of the rapid change in diffusion rate expected in this range. Between 900 F and 1000 F, the diffusion coefficient increases by an order of magnitude (Ref. 4) and the solubility limit increases about 50% (Fig. 2).

Calculations showed that holding at 850 F would deplete a 7 microin. coating in about 5 h, but at 1000 F only about 4 min would deplete the same. This rapid change with temperature was of concern because for large production parts as much as 10 min or more might elapse in heating between 900 F and the eutectic temperature of 1018 F. Therefore, a series of tests was considered necessary to determine how much copper is depleted during heating to the eutectic temperature, and if the 20 microin. target value would be sufficient to survive heating and provide a liquid for bonding.

The effect of the heating cycle was evaluated by heating 0.006 in. thick 1100 aluminum samples, which had been coated by physical vapor deposition on one side with 16 microin. of copper, to several temperatures below the eutectic temperature. The diffusion specimens were heated to 900 F at a rate of 20 F/min, and then at about 7 F to the maximum temperature. When the preselected temperature was reached, the specimens were immediately cooled to room temperature and then analyzed by electron microprobe line scans and raster images to determine how much of the copper had been depleted. One sample, used as a control, was held at 1000 F for 60 min to deplete the coating entirely.

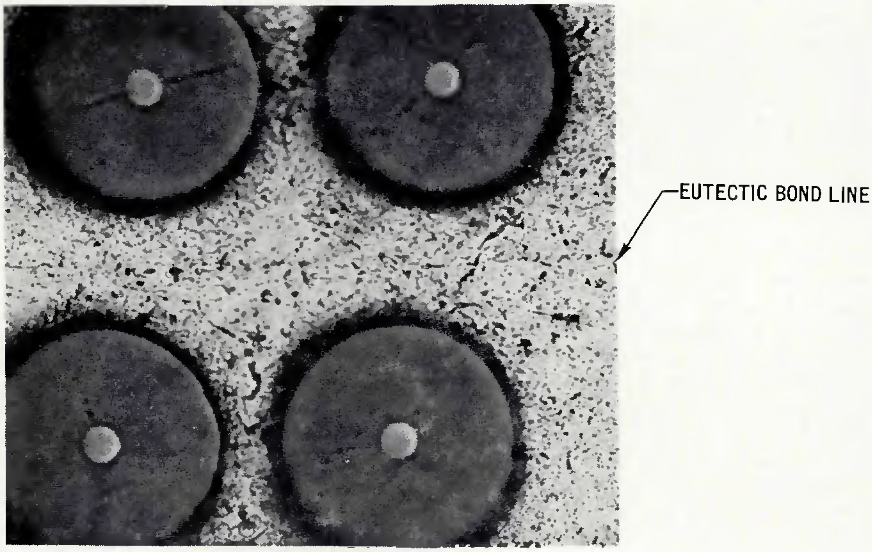
Results of representative microprobe analyses are shown in Fig. 6. The x-ray rasters and line of scans show that the 16 microin. thick copper coating was completely diffused in the 1000 F/60 min treatment as expected. Some diffusion occurred as a result of heating to 900 F and 1000 F, with the higher temperature resulting in significantly more diffusion. The line scans were used to estimate the amount of copper depleted from the coating. This was accomplished by measuring the areas under the concentration curves and determining the ratio of the area of the heating cycle in question to that of the completely diffused sample (curve C, Fig. 6). This ratio multiplied by 16 microin. — the original thickness of the completely diffused coating — provided the amount of coating lost during heating. The coating loss was calculated to be:

Test Temp.	Depleted Zone
900 F	1.98 microin.
1000 F	8.05 microin.

These data for 0.006 in. aluminum foil indicated that about 8 microin. of copper would be lost in heating to 1000 F and it was estimated that probably another 2 or 3 microin. would be lost in reaching the eutectic temperature. A smaller loss would be encountered with a composite monolayer because the matrix would be equivalent to a thinner (~.0045 in.) aluminum foil which would be coated on two sides rather than just one. Consequently, diffusion completely through the thickness would be expected. This would lower the concentration gradient and reduce the rate of diffusion. On this basis, a coating thickness range from 17.5 to 22.5 microin. (20 microin. nominal) was selected for eutectic bonding B/Al. This amount would provide a liquid film between about 100 and 160 microin. thick even with the loss of 10 microin. of copper per surface during heating. This amount was considered adequate since bonding would be done under pressure to provide good contact between adjacent monolayer foils.

In order to verify the adequacy of the selected coating thickness range, 1 × 1 in. laminates were prepared from B/Al monolayer foils coated with 14-20 microin. of copper and heated within the eutectic bonding temperature range of 1030 F and held from seven to fifteen minutes at temperature. The as-bonded samples were characterized by droplets of solidified Cu/Al alloy along the edges where liquid had been squeezed out of the joint during bonding. Electron microprobe analyses were made to determine if $CuAl_2$ was present at any of the bond lines. These analyses showed that the bonds essentially were free of intermetallic compound except in the form of discrete, isolated particles. Chemical analyses showed the average copper content of the aluminum matrix was about 2%.

The typical microstructure shown in Fig. 7 was a result of isothermal solidification at the bonding temperature when all the copper was taken into solution in the solid aluminum. On cooling, most of the copper was precipitated as fine, randomly distributed particles of $CuAl_2$. Some agglomeration of the precipitates occurred which can be seen on the x-ray raster image. Microprobe line scans



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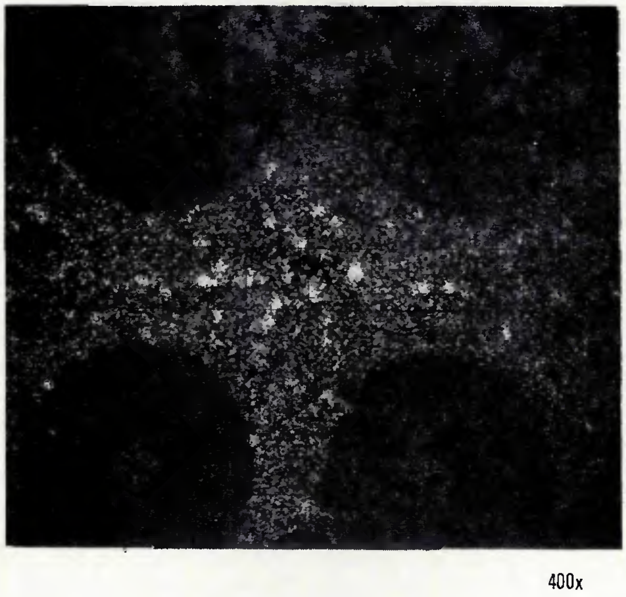

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Fig. 7 — Eutectic bonded joint in boron-aluminum laminate (reduced 17%)

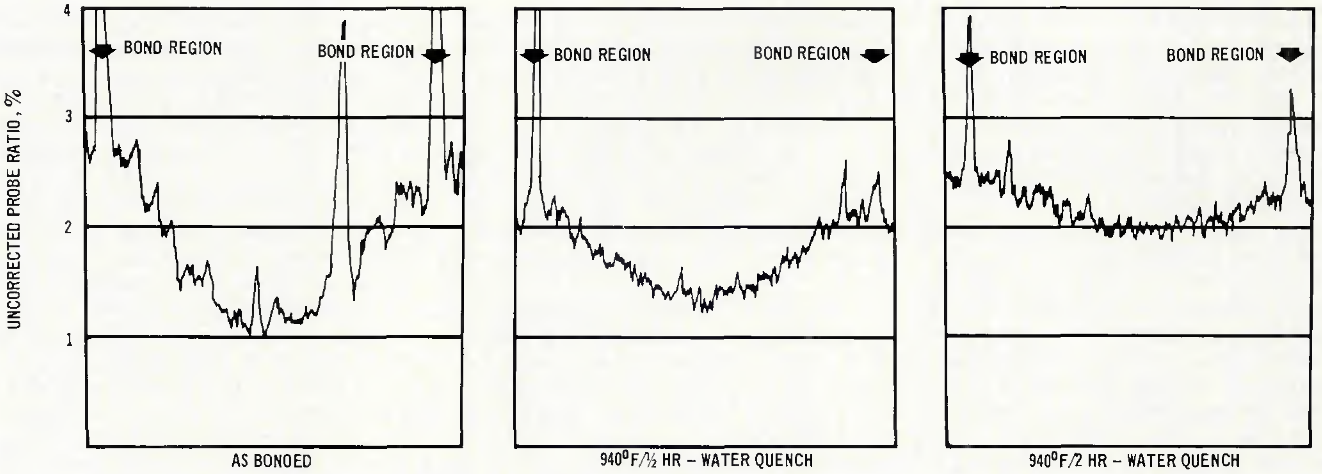

Fig. 8 — Electron microprobe line scans showing effect of postbonding heat treatment on the distribution of copper in the matrix of eutectic bonded boron-aluminum composite laminate

showed a copper concentration gradient existed from bond lines to the center of the monolayer foils.

A study was undertaken to determine if a more homogenous structure might be obtained by heat treatment. This possibility was evaluated by subjecting 4 ply laminates to postbonding heat treatments and then conducting microprobe line scans to determine copper distribution. The microprobe scans in Fig. 8 show the pronounced gradient between bond lines in the as-bonded condition with numerous sharp peaks indicating localized areas of copper enrichment. A solutioning treatment at 940 F for 30 min appeared to narrow the gradient and reduce the tendency for the compound to agglomerate. Increasing the time at temperature from 30 min to 2 h produced a further improvement in copper distribution.

These studies showed that the copper distribution within the aluminum matrix could be improved by post-bonding heat-treatment. However, localized areas of copper segregation were not eliminated completely under any of the conditions evaluated. Even in the as-bonded condition the lack of homogeneity did not appear severe enough to be detrimental to composite properties. Therefore, post bonding heat-treatments were not considered essential to the eutectic bonding process.

As a final check on the suitability of the 20 microin. coating thickness, the strength of eutectic bonded joints was evaluated by short-beam interlaminar shear tests. Details of the specimen design are shown in Fig. 9. With this type specimen, interlaminar shear strength is determined from the expression:

$$\gamma = 3/4\ (P/bh)$$

where:

P = applied load at center of beam

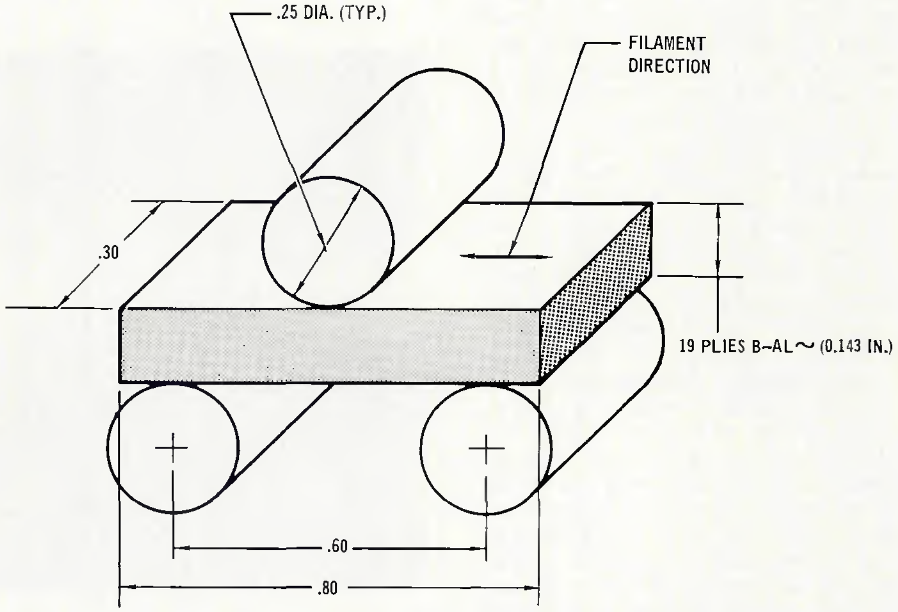

Fig. 9 — Configuration and test setup for short-beam interlaminar shear specimens

Table 3 — Typical Properties of Eutectic Bonded Boron-Aluminum [a]

Type of loading	Ultimate strength, ksi at R.T.	Ultimate strength, ksi at 600 F	ultimate strain, microin./in. at R.T.	ultimate strain, microin./in. at 600 F	initial modulus 10^6 psi at R.T.	initial modulus 10^6 psi at 600 F
Longitudinal tension						
coupon	160	155	6500	5800	29.8	28.1
beam	194	—	7200	—	28.7	—
Longitudinal compression						
beam	343[b]	—	10500	—	36.8	—
Transverse tension						
coupon	16.7	3.9	4200	6500	19.5	14.0
Transverse compression						
beam	37.5	9.6	2400	10700	20.0	17.4
In-plane shear						
rail shear	10	3.7	16000	13000	10.0	7.8

(a) All tests conducted on 42-45 v/o B/Al
(b) Failure occurred in honeycomb core—no failure in B/Al face sheet

b = beam width
h = beam depth

However, the actual stress distribution within a short-beam specimen may differ significantly from that predicted by the above expression. Therefore the test was used solely to determine if the bond line would fail by shear. All of the specimens tested failed by flexural tension rather than by shear. At the failure loads, the calculated shear stress on the bond lines exceeded an average value of 10,000 psi. These tests provided further evidence that eutectic bonds made with 20 microin. of copper were strong and of good quality.

Co-Bonding of Titanium and Boron-Aluminum

One of the unique advantages of eutectic bonding proved to be its ability to incorporate local reinforcement in the form of titanium interleaves during the normal processing of boron-aluminum laminates. Interleaving significantly improves matrix dependent properties, particularly at elevated temperature, in the following areas:

- Mechanical joint bearing strength
- Ultimate transverse strain capability
- Shear strength of cross-plied (± 45 deg) laminates
- Crippling strength at elevated temperature
- In-plane shear strength of unidirectional laminates

When structural analysis indicated the advantages to be gained from local reinforcement, tests were initiated to determine if titanium interleaves could be incorporated into boron-aluminum laminates during eutectic bonding. Initial tests were made on a multi-ply laminate consisting of copper coated boron-aluminum and bare Ti-6Al-2Sn-4Zr-2Mo alloy. The lay-up contained three plies of boron-aluminum interleaves with two plies of 0.012 in. thick Ti alloy. Metallographic examination was used to evaluate the joint and showed the bond to be continuous and of high quality with an interaction zone less than 40 microin. thick (Fig. 10). Microprobe analyses were made to determine the depth of copper diffusion into the titanium. No evidence of copper was detected beyond the interaction zone.

Because the initial results were encouraging, the evaluation was extended to determine the interlaminar shear strength between the Ti alloy and boron-aluminum. For these tests, specimens of the type shown in Fig. 9 were cut from a multi-ply laminate and tested in three point bending. The basic laminate contained nineteen plies, of which three were Ti-6Al-2Sn-Zr-2Mo alloy. These Ti plies were located in the center of the laminate and were separated from each other by a single boron-aluminum ply.

Five interlaminar shear specimens were tested at room temperature. Failure loads ranged from 1190 to 1210 lb and the average was equivalent to a nominal shear strength in excess of 16,000 psi at the titanium alloy-boron-aluminum interfaces. However, all the specimens failed in tension and the failures originated in the outer boron-aluminum plies at stress levels in excess of 160,000 psi. On the basis of tese tests, it was concluded that titanium interleaves could be included in a boron-aluminum laminate during a normal eutectic bonding cycle.

Subsequent tests showed that adding one titanium ply, 0.008 in. thick, for each four boron-aluminum plies increased the transverse tensile strength by a factor of three while increasing the strain-to-failure about three times to about 1.2%. Additional tests were made to demonstrate the improvement in bearing strength that could be attained by interleaving. Test specimens were 1.5 in. wide × 9 in. long with 0.312 in. diam fastener holes centrally located 0.75 in. from each end. These samples contained 28 plies of boron-aluminum (0.0075 in./ply) and 8 plies of Ti-6Al-4V alloy (.012 in./ply). These specimens failed at an average load of 14,000 lb in a combined tension/shear mode. A pure boron-aluminum specimen of equivalent weight would withstand only about 4,000 lb before failure. These and other test results indicate that the inclusion of titanium interleaves is a major advancement in boron-aluminum.

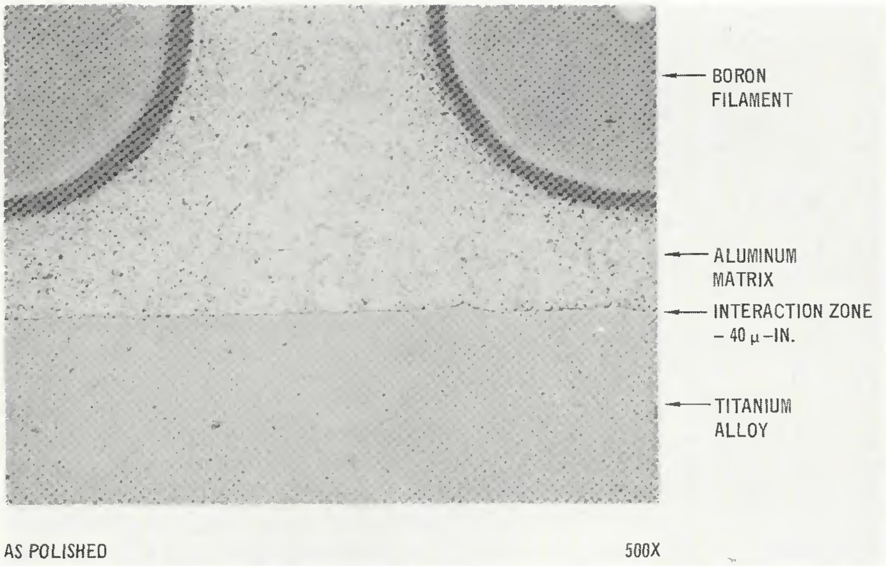

Fig. 10 — Titanium joined to boron-aluminum by Al-Cu liquid formed during eutectic bonding cycle (reduced 24%)

Determination of Mechanical Properties

During the development of the eutectic bonding process, more than 500 mechanical property tests were conducted. Initially, bonded tensile coupons were tested to verify that eutectic bonding could be used to produce laminates with the high properties generally offered by B/Al. Once the critical processing parameters were defined and process feasibility demonstrated, a comprehensive program was undertaken to establish design allowable mechanical properties. Both transverse and longitudinal properties were determined at room temperature and 600 F. Properties of interest include ultimate tensile strength, strain to failure, modulus of elasticity, shear strength, crippling strength. A full description of this phase of the investigation including the test techniques, specimen designs, and test variables is beyond the scope of this paper. However, some of the test results are summarized in Table 3. These data demonstrate that the high strength, high modulus, low density potential of B/Al can be attained in laminated structures fabricated by eutectic bonding.

Summary

The results of the initial investigation showed that boron-aluminum laminated structures can be fabricated by coating the monolayer foils with a copper layer about 20 microin. and heating in the temperature range from 1030 F and 1060 F. Unacceptable degradation can be avoided by restricting the bonding time to less than fifteen minutes at the low end of the range and seven minutes at the high end.

Eutectic bond lines characteristically are free of brittle compounds that would lower joint strength. If present, these compounds exist as discrete, widely spaced particles. The very high interlaminar shear strength of eutectic bonded joints and the fact that joint failures have seldom been observed attest to their high over-all quality. Further evidence is given by the good mechanical properties measured on eutectic bonded B/Al laminates.

Eutectic bonding was also found to be a versatile process in that it was readily adaptable to the inclusion of titanium interleaves. The ability to utilize local reinforcement had eliminated concern over the inherently low shear transfer and bearing capability of B/Al. On the basis of these encouraging results, work was initiated to develop the production techniques needed to fabricate large, complex boron-aluminum structures. The development of such processing techniques along with the fabrication of complex structures is the subject of Part II of this paper.

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