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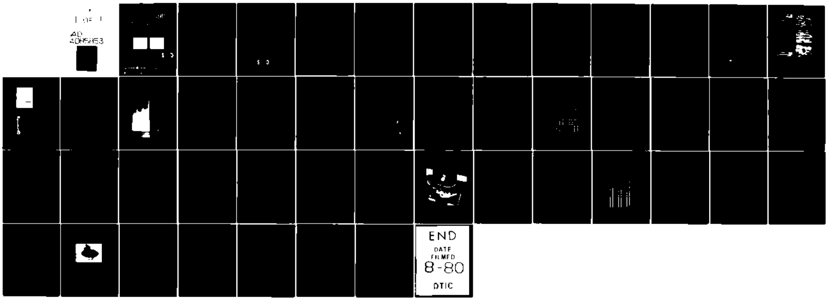


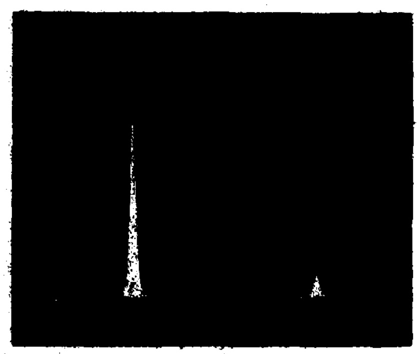
METAL MATRIX COMPOSITE BONDING CHARACTERISTICS AND IMPACT PROPERTIES

By

Dr. Robert G. Carlson
GENERAL ELECTRIC COMPANY

FINAL REPORT

30 APRIL 1980



For

Dr. A.H. Rosenstein
DEPARTMENT OF THE AIR FORCE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
BOLLING AIR FORCE BASE, D.C. 20332

GENERAL ELECTRIC

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This research program objective is to develop an understanding of the surface characteristics and bond behavior in metal matrix composites as related to the impact properties. Dr. A. H. Rosenstein of the Office of Scientific Research (AFSC) is acknowledged for his support of this research.

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The initial part of this program addresses itself to bonding of aluminum foils with different surface treatments. Scanning electron micrographs revealed the presence of Al/Fe compounds. Following this, extensive efforts were directed at identifying an etchant to remove such hetrogeneous phase identified to be an aluminum iron compound, Al_3Fe. After an extensive literature review, three chemical etchants were selected, the aluminum alloys foils were chemically tested, and the etched foils were evaluated by scanning electron microscopy. Single layered monotapes were then formed and evaluated by bond integrity testing (BIT). Following this, further studies were performed on evaluation of hybrid metal/metal foil combinations consisting of aluminum alloy foils against titanium or stainless steel foils. The study was next directed at fabrication of single-ply boron/aluminum panels and then in formation of hybrid titanium/aluminum/boron (TAB) and stainless steel/aluminum/boron (SAB) single-ply panels. The fabricated bonded monotapes (BMT) were consolidated into 8-ply panels, tested by bend and impact testings, then evaluated metallographically. Finally, based upon the results, 50-ply panels were vacuum hot press consolidated, machined into Charpy impact specimens and evaluated by instrumented impact testing.

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Mr. A. C. Losekamp of the Material and Process Technology Laboratories consolidated the tapes and panels along with monitoring the testings. The support of Dr. A. H. Rosenstein of the Air Force Office of Scientific Research, who had funded this work is gratefully acknowledged. Further, the author acknowledges Dr. T. Nicholas of the Air Force Materials Laboratory, Wright Patterson Air Force Base, for conducting a portion of the impact testing.

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AND IMPACT PROPERTIES

Dr. R. G. Carlson

INTRODUCTION

One major obstacle to the realization of composite material's full potential has been the relatively low tolerance to impact or foreign object damage (FOD).(1) Achieving a high tolerance to impact requires a basic understanding of the surface characteristics. Typically, a composite structure is fabricated by bonding together a sequence of filament laminate plies. Each ply consists of a single layer of filaments suitably anchored in a mother matrix. Under improved processing conditions, the degree of bonding can be extensive, resulting in a more rigid structure with lower tolerance to impact. Since the mother matrix cannot absorb much energy through deformation as a result of integral matrix/filament bonding, substantially all loading is carried by the relatively hard, brittle reinforcement filament. Filament fracture generally leads to structure failure. Higher impact-resistant composite materials, on the other hand, do not possess the bondability of the more ductile materials. If the degree of bonding is optimized, the laminates tend to slide with respect to each other much in the manner of a deck of cards coated with honey. However, as the degree of bonding is further decreased, excessive sliding occurs and the ability to absorb impact energy greatly decreases. Thus, it is desirable to characterize the "toughness" of a composite by activating various energy-absorption mechanisms. Five active identifiable mechanisms which dissipate the impact energy include: (1) matrix deformation (U_m), (2) matrix/matrix debond ($U_{m/m}$), (3) filament/matrix debond ($U_{f/m}$), (4) filament fracture (U_f), and (5) filament pull-out ($U_{p/o}$). An analytical expression for the absorption of energy is:

$$\Sigma U = U_m + U_{m/m} + U_{m/f} + U_f + U_{p/o}$$

As described above, initially, bonding energy increases and energy absorption increases. However, as the degree of bonding increases further, there is a reversal, and the ability to absorb impact energy decreases and the structure takes on a more "brittle" nature.

A representative of the impact energy absorption of a composite is schematically shown in Figure 1.(2) Here it can be noted that as the shear strength increases, the bondability increases. Simultaneously, however, as the shear strength increases, the fracture resistance decreases. A balance of these composite behaviors is required.

As an integral part of this study, boron filaments have been composited with 1100 Al, 2024 Al, and 5052 Al matrices to form monotape specimens. These monotapes initially consisted of aluminum foils bonded together with different surface treatments, and later, bonded to titanium and stainless steel foils.

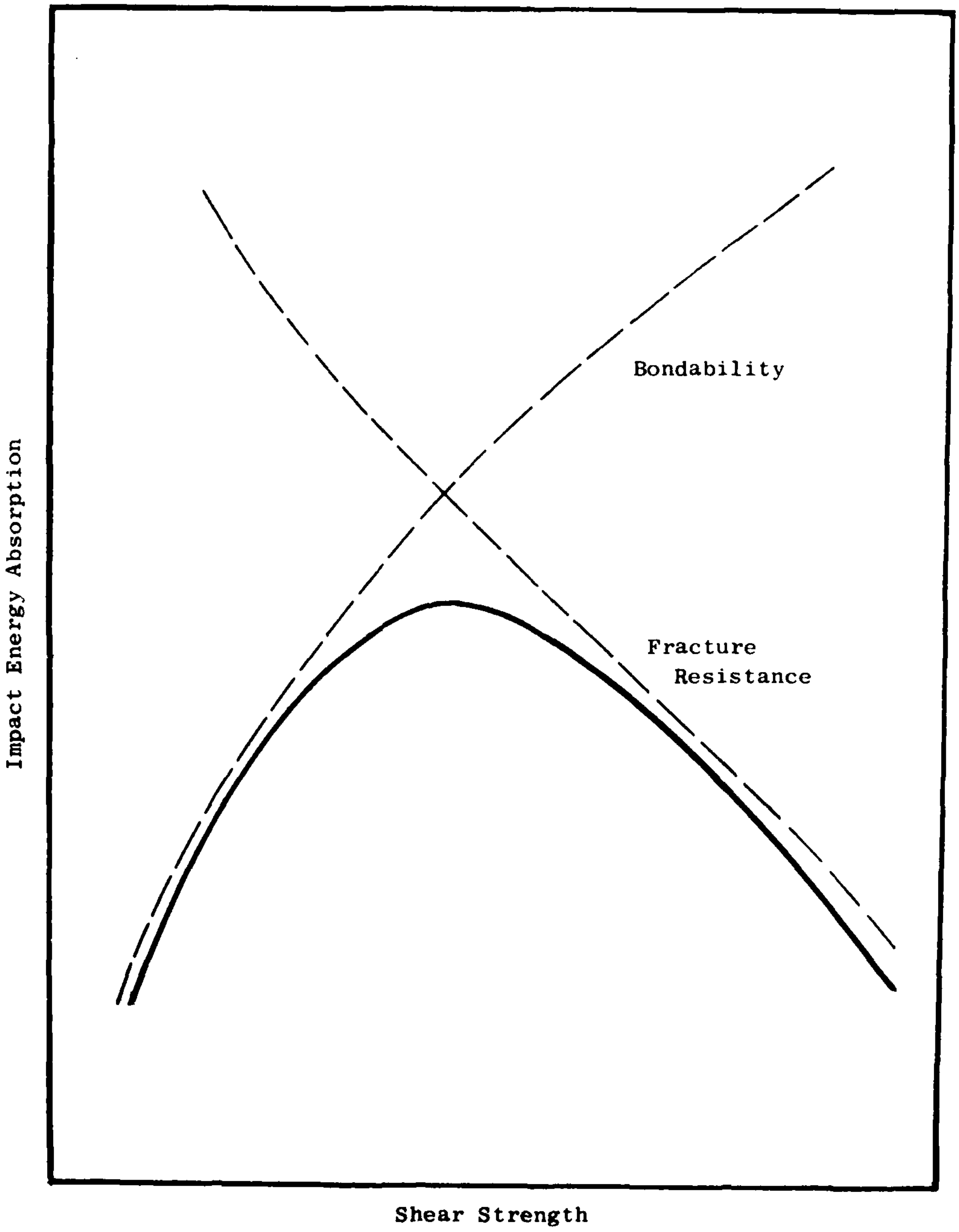

Figure 1. Schematic of Impact Energy Absorption as a Function of Bond or Shear Strength.

In previous studies,[3] failures were observed to occur at the boron/aluminum interface, indicating a weaker intraply region. The intent of this study is to increase intraply (boron/aluminum interface) bond while maintaining or further enhancing interply (metal to metal) bond and achieving higher impact properties. Hence, a balance is required between these bond characteristics.

EXPERIMENTAL

Mechanical Surface Preparation

Surfaces of three aluminum alloys (1100 Al, 2024 Al, and 5052 Al) have been prepared with four degrees of surface abrasion: none, light, intermediate, and severe, as seen in Figure 2. Single-ply panels consisting of two prepared sheets have been bonded with a localized pressure procedure at 920°F/6 ksi/30 minutes. Specimens have been cut from these pressed panels and evaluated by the bond integrity test (BIT), a modified peel test.

Scanning electron microscopy of specimens (see Figure 3) show the fragmented nature of these surfaces as a result of the abrasion. It appears that extensive surface exfoliation has occurred. The BIT test results reveal that no bonding is evident on the 1100 Al with surfaces that were either with the as-received or the light abrasion treatment. The intermediate treatment on the 1100 Al produced an average bond strength of 0.44 lb/in., while the severe abrasive treatment produced a bond strength of only 0.25 lb/in. It was determined that the bond strength of the 2024 Al in the "none" abrasive treatment had an average bond strength of 22.0 lb/in., while the average bond strength of the 5052 Al was 12.0 lb/in. Hence, these results show that 1100 Al alloy bonds are less than 5 percent that produced between 2024 Al and the 5052 Al.

From this study, the intermediate abrasive (IA) treatment was selected for mechanical surface preparations and is designated as the 3M treatment in all subsequent investigations.

Chemical Surface Preparation

Chemical surface treatments of alkaline cleaning, acid deoxidizing/etching and final surface etch or fixing operation have been applied to the three aluminum alloys. Scanning electron micrographs reveal that extensive pitting can be achieved on the 1100 Al alloy and the amount of pitting, which may correlate to the degree of bonding, has been observed to occur more with increased cleaning and etching times. Also observed by an EDAX (Energy Disbursive Analysis of X-rays) element identification technique is the presence of an Al/Fe compound which appears to be originally embedded in the matrix. It has been noted that these particles, after surface treatment, are more readily delineated, as seen in Figure 4.

Similar particles are noted also in the surfaces of the 2024 and 5052 Al foils. However, electron microprobe reveals a different makeup of these particles. The particles in 1100 Al are comprised of an Al/Fe ratio of about 8/1, while in the 5052 Al, this Al/Fe ratio is about 25/1. The particles in the 2024 Al, on the other hand, do not contain Fe, but rather Cu. This Al/Cu

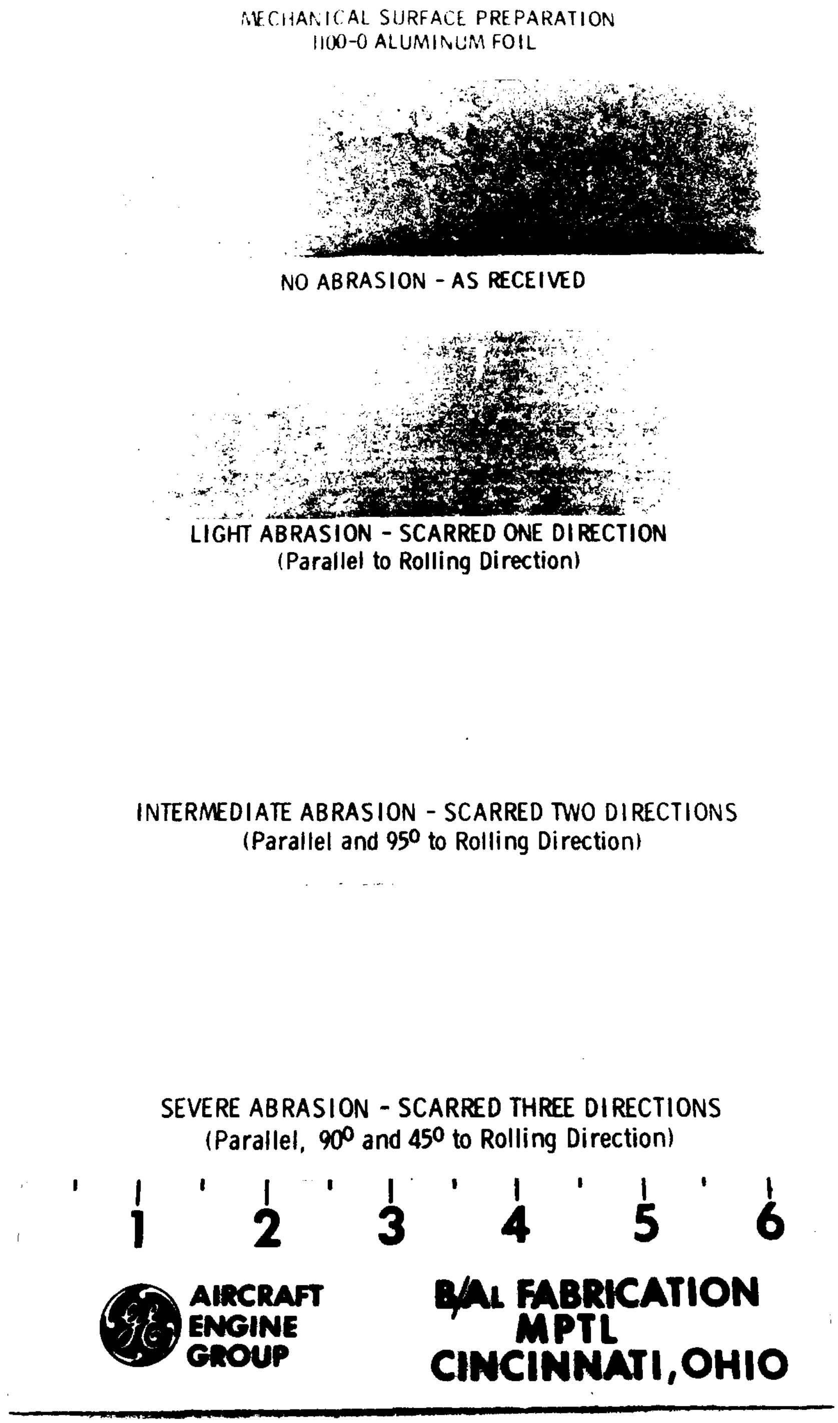

Figure 2. Mechanical Surface Preparations of Aluminum Foil.

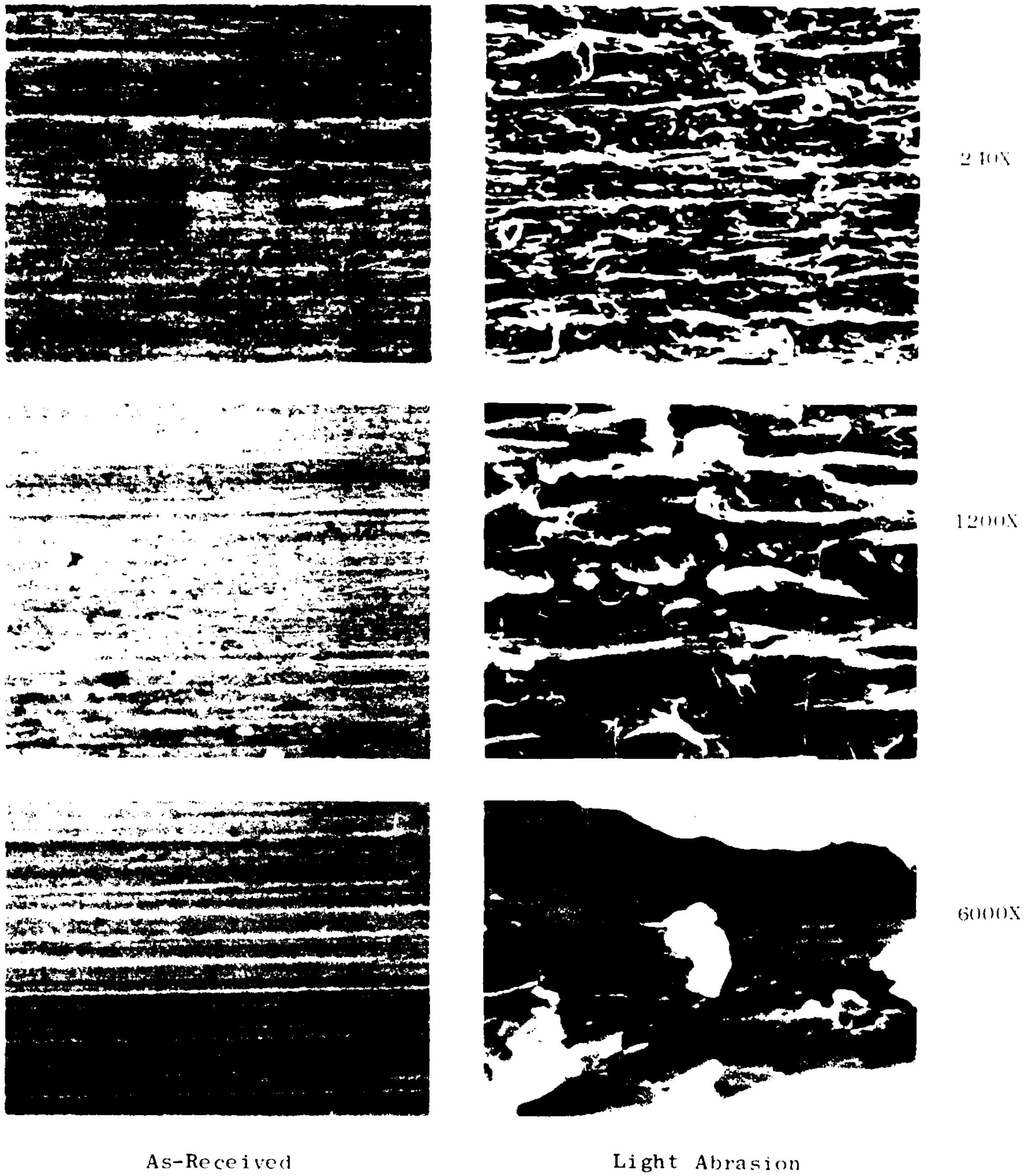

Figure 3. Scanning Electron Micrographs of 1100 Al Foil in the As-Received and Light Abrasion Conditions. The Surface After Mechanical Abrasion Reveals Exfoliated Characteristics.

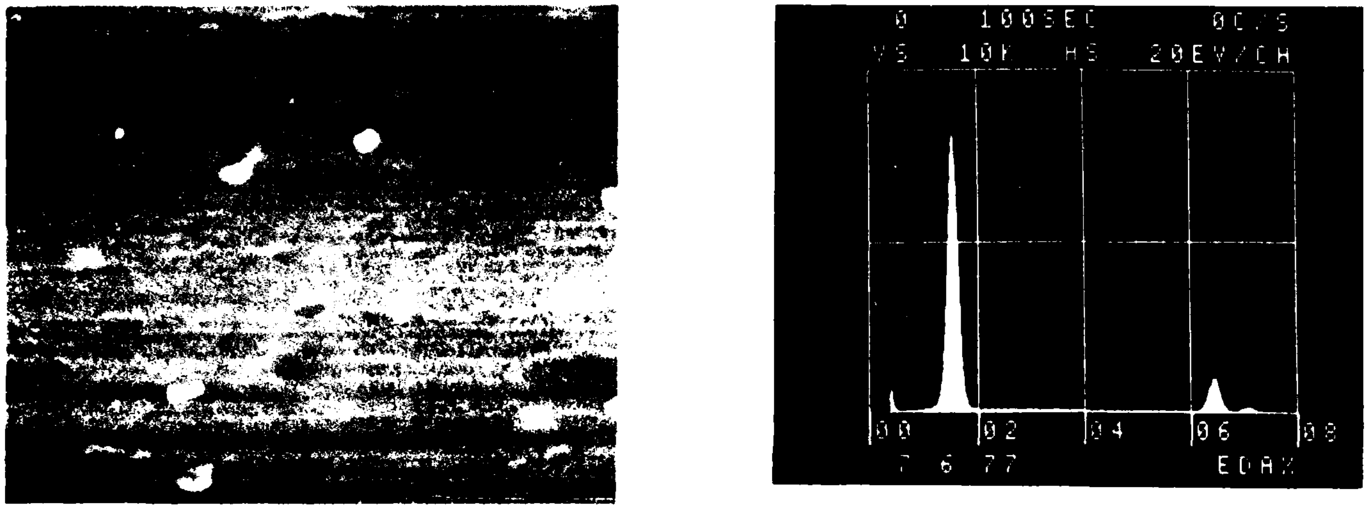

Figure 4. Etched Surface of 0.002 inch 1100 Al Alloy Sheet Delineating Aluminum-Iron Particles at 6000X (Left). Element Identification Trace (Right) Focused on Particles Distinguishes Presence of Only Aluminum and Iron Peaks.

ratio is more on the order of 20/1. One other interesting observation of the 2024 Al alloy was that, after the etching operation, these Al/Cu particles were completely removed, leaving only a pitted surface. At this point, it would be somewhat speculative to detail the nature of these plate-like particles, but it is believed that they are intermetallic compounds such as Al_3Fe or Al_6Fe which have been worked by the rolling operations into the Al alloy surfaces.[4]

To increase the aluminum/aluminum bond characteristics, the surface additional chemical surface treatments were investigated. The intent of this effort was not only to remove prevalent surface oxides, but also to pit the surface to achieve a more uniform bond structure. It was felt that these intermetallic surface particles were of interest since it was believed that they interferred with bonding.

This work addressed itself to identifying an etchant to remove this heterogeneous surface phase. After an extensive review of the literature, three chemical etchants were selected, the foils were chemically treated, and the etched foils were evaluated by scanning electron microscopy. Single layer monotapes were then formed and evaluated by bond integrity testing (BIT). Details on this investigation are presented later in Metal/Metal Monotapes.

Boron Filament Surface Preparation

Three boron surface treatments were evaluated. The first, our standard procedure, was to clean the filament by passing it through an in-line trichloroethane bath. Two surface deposition procedures have been established for coating the boron filaments. The first was the vapor deposition of unalloyed aluminum. To accomplish this, the filaments were initially wound on an aluminum foil. The surface of the winding was then covered with another aluminum foil and the assembly vacuum hot-press, bonded at 860°F into a monotape. A three inch by eight inch section was then selectively etched to remove the outer Al, exposing the aligned boron filaments. These filaments subsequently were simultaneously coated by vacuum vapor deposition with unalloyed aluminum, as seen in Figure 5.

Essentially the same procedure was used to coat the boron filament surface with a chemical conversion coating (Alodine). The exact nature of this coating is not known but has been identified to be an oxide mixture of phosphorus, chromium, and boron. Application of this coating and subsequent heat treatment at bonding temperatures show no degradation of the boron filament.

Single-ply sandwich panels were prepared and evaluated by BIT testing. Results revealed the Alodine coating to exhibit the lowest bond with the Al coating intermediate to the Alodine and the standard preparation. In addition, an attempt was made to further increase the intraply bond by a combination of the S/F 9 treatment on one sheet with the intermediate abrasion (IA) on the other. This resulted in only a 5 percent increase in bond strength. From this study, the standard trichloroethane cleaning was selected for evaluation in the eight-ply panel specimens.

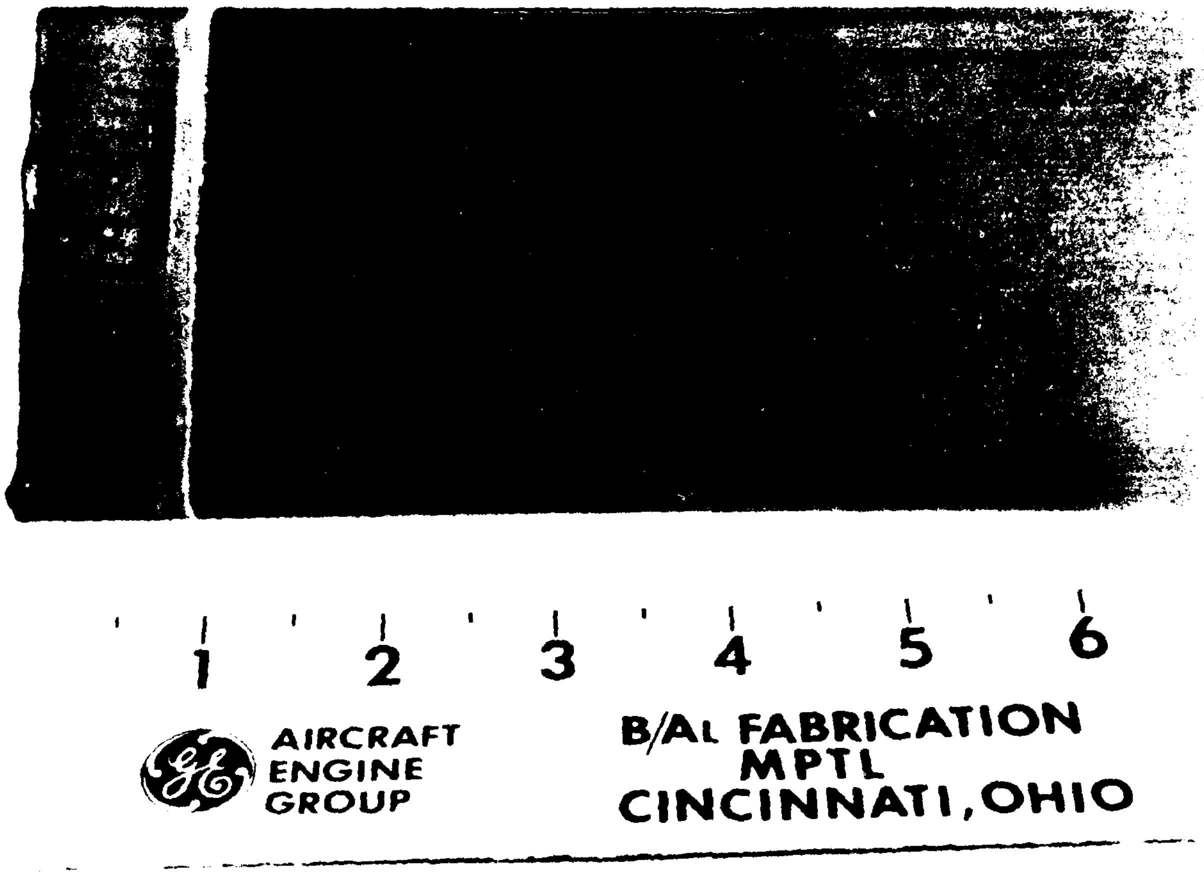

Figure 5. Collimated Boron Filaments with the Aluminum Matrix Foil Etched Away and the Center Section Cleaned and Coated.

Metal/Metal Monotapes

The surfaces of the aluminum foils were carefully prepared and sectioned into three inch by five inch specimens. Three specimens (one from each of the three alloys: 1100 Al, 2024 Al, and 5052 Al) were measured for thickness and then subjected to our standard surface treatment (S/F 9) consisting of an etchant cleaner, followed by a water rinse, then a deoxidizer, another water rinse, and finally a dip in a fixant and air dried. Figure 6 shows the sequence of events to produce the standard S/F 9 surface treatment.

As mentioned earlier, three chemicals were evaluated to remove the Al_3Fe particles embedded in the aluminum surface. These three etchants, shown in Table 1, were designated A, B, and C. The times investigated with the chemical etchants were 15 seconds, 30 seconds, and 60 seconds. These special Al_3Fe etching chemicals were employed following the water rinse after the deoxidizer step. The aluminum foils were then given another water rinse, and in the same manner as the S/F 9 treatment, they were given the fixant treatment and air dried. Thickness measurements on the nominally 0.002 inch thick foil showed that for the 1100 Al, the standard S/F 9 treatment removed about 0.00005 inch. The 60 second treatment of etchant "B" removed an additional 0.00002 inch, and the 60 second treatment of etchant "C" removed an additional 0.00003 inch. The same treatments of the 5052 Al alloy exhibited similar thickness changes, while treatment of the 2024 Al showed negligible thickness changes. These thickness measurements confirm our previous results that very small (if any) thickness changes occur as a result of the chemical surface preparation.

Scanning Electron Microscope (SEM) studies were performed on all of these prepared surfaces. The surface with the standard S/F 9 treatment revealed (as before) the presence of Al_3Fe particles determined from EDAX evaluation. The 1100 Al surfaces treated with etchant "A" and "C" were only partially effective in removing the particles; while as seen in Figure 7, it was concluded that etchant "B" was very effective in dissolving away the Al_3Fe particles.

Based upon these results, a series of single-ply metal/metal peel specimens were prepared with select treatments as shown in Table 2. This study was directed at the bond behavior between metal combinations. The first series was to identify the bond behavior employing the special etch "B" (designated C/L B30) to promote better bonding between 1100 Al to 1100 Al. Three, three inch by five inch 1100 Al specimens were prepared. The first couple was bonded with the 3M scarred surface interface against the as-received (after an acetone cleaning) surface. The second cycle was bonded with the 3M scarred surface interfaced against the standard S/F 9 treated surface. The third couple contained the 3M scarred surface and was interfaced against the surface given the added treatment of 30 seconds with the "B" etchant. Two specimens were prepared in which the 1100 Al was bonded to a 2024 Al and a 5052 Al foil.

The peel test results, which represent an average of three individual tests, reveal that the additional etchant C/L B30 surface treatment did not

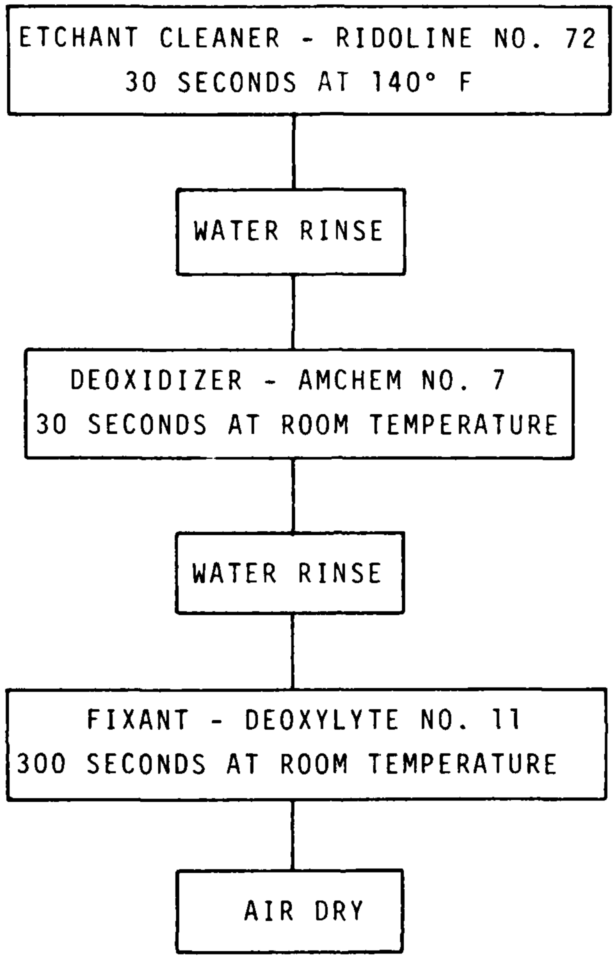

Figure 6. S/F9 Surface Treatment to Prepare the Aluminum Foil for Bonding.

Table 1. Special Chemical Etchants for Removal of Al_3Fe Particles.

A - 550 ml (96% H_2SO_4) + 280 ml (85% H_3PO_4) + 170 ml (79% HN_3)

B - 940 ml (H_2O) + 55 ml (79% HNO_3) + 5 ml (49% HF)

C - 995 ml (H_2O) + 5 ml (48% HF)

Table 2. Bond Integrity Tests on Metal/Metal Single Ply Monotapes Bonded at 920° F/6 ksi/30 Minutes.

Specimen No.	Material Combination	Surface Treatment	Bond Strength (lb/in.)
1	1100 Al (0.002" Thick) to 1100 Al (0.0002" Thick)	3M Scarred / As-received	0.72
2	1100 Al (0.002" Thick) to 1100 Al (0.002" Thick)	3M Scarred / Standard S/F9	2.04
3	1100 Al (0.002" Thick) to 1100 Al (2.002" Thick)	3M Scarred / Special Etch "B"	1.28
4	1100 Al (0.002" Thick) to 2024 Al (0.002" Thick)	3M Scarred / As-received	14.0+(1)
5	1100 Al (0.002" Thick) to 5052 Al (0.002" Thick)	3M Scarred / As-received	14.0+(1)

(1) Specimen did not peel, tore through 1100 Al.

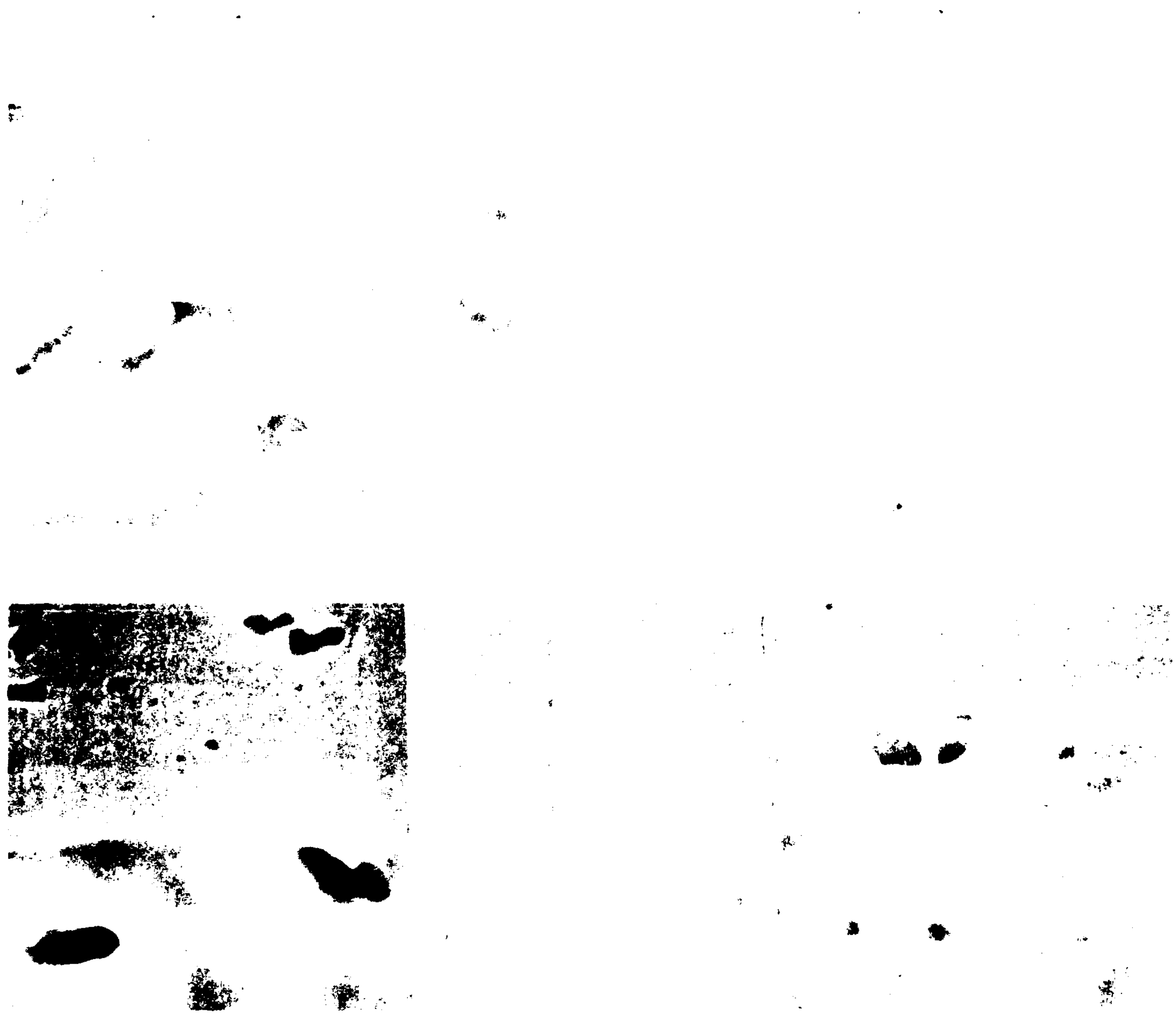

Figure 7. Scanning Electron Micrographs of 1100 Al Surface After Surface Treatment. Top is Furface with Al_3Fe Particles After Standard S/F9 Treatment. Bottom Shows Removal of Al_3Fe Particles After C/L B30 Etch. (6200X)

improve bonding. This was surprising, since it had an SEM surface structure deemed more conducive for better bonding. Several specimens with this special treatment were hand-peeled and found to give off a distinct odor. It was conjectured that some residual etchant may have been entrapped in the etched-away Al_3Fe cavities. As an added effort, another series of foils was given the C/L B30 treatment. In this instance, the surfaces were ultrasonically cleaned after the surface treatment; however, these foils disintegrated during this cleaning procedure.

Peel test results on 1100 Al specimens bonded against 2024 Al and 5052 Al reveal excellent bonding. The bonded surfaces could not be peeled apart; rather, the 1100 Al foils tore at the bond location. Hence, it can be concluded that the 1100 Al bonded to either 2024 Al or 5052 Al produces extensive bonding.

Further studies have been directed at evaluation of hybrid foil combination consisting of aluminum alloy foils against titanium or stainless steel foils. In this effort, select surface foil treatments are evaluated in formation of boron/matrix monotapes and their consolidation into multilayer composites.

In the initial part of this study, foils of the three aluminum alloys (1100 Al, 2024 Al, 5052 Al), and a fourth aluminum alloy (6061 Al), along with AISI 316 stainless steel and the unalloy titanium were prepared as shown in Table 3. Based on our previous work, the surface preparation of all aluminum alloys was by 3M intermediate roughening procedure. For both the 316 stainless steel and the titanium , three preparations were used: (1) the 3M, (2) grit blasting, both light and heavy, and (3) a perturbed surface generated by a electrical discharge weld. In the electric discharge perturbed surface preparation, the three patterns evaluated were the 1/4 inch pattern, the 1/8 inch pattern, and the 1/16 inch pattern. Combination of the aluminum alloys were mated against the stainless steel and the titanium and vacuum hot-pressed at two conditions of 875°F/5 ksi/30 minutes and 900°F/5 ksi/30 minutes.

A summary of the peel strengths of the bonded tapes for thirty select systems are recorded in Table 4 and plotted on the bar chart in Figure 8. In general, the 1100 Al foils bonded to the stainless steel foils produced consistently low bond strengths. The highest bond strength with stainless steel are obtained with the 5052 Al alloy. Again, as with the stainless steel, the 1100 Al bonded to the unalloyed Ti produced the lowest average bond strengths; however, these bond strengths were five to ten times greater than with the stainless steel bond. Further, bonding of the 5052 Al alloy against the Ti produced the highest average strength. It was also noted that the grit-blast treatment of the Al alloy gave consistently high bond strength values while the 1/16" perturbed surface produced reasonably high bond strengths.

From the results of these bonded metal/metal monotapes, boron reinforced tapes were formed as detailed in the next section.

Table 3. Material and Surface Preparation

ALLOY	SYSTEM ID NO.	MATERIAL	THICKNESS	SURFACE PREPARATION
Al	A	1100	.002"	3M
	B	6061	.002"	3M
	C	2024	.002"	3M
	D	5052	.002"	3M
SS	1.	SS	.002"	3M
	2.	SS	.002"	Grit Blast-Light
	3.	SS	.002"	Grit Blast-Heavy
	4.	SS	.002"	Perturbed-1/4" pattern
	5.	SS	.002"	Perturbed-1/8" pattern
	6.	SS	.002"	Perturbed-1/16" pattern
Ti	7.	Ti	.002"	3M
	8.	Ti	.002"	Grit Blast-Light
	9.	Ti	.002"	Grit Blast-Heavy
	10.	Ti	.002"	Perturbed-1/4" pattern
	11.	Ti	.002"	Perturbed-1/8" pattern
	12.	Ti	.002"	Perturbed-1/16" pattern

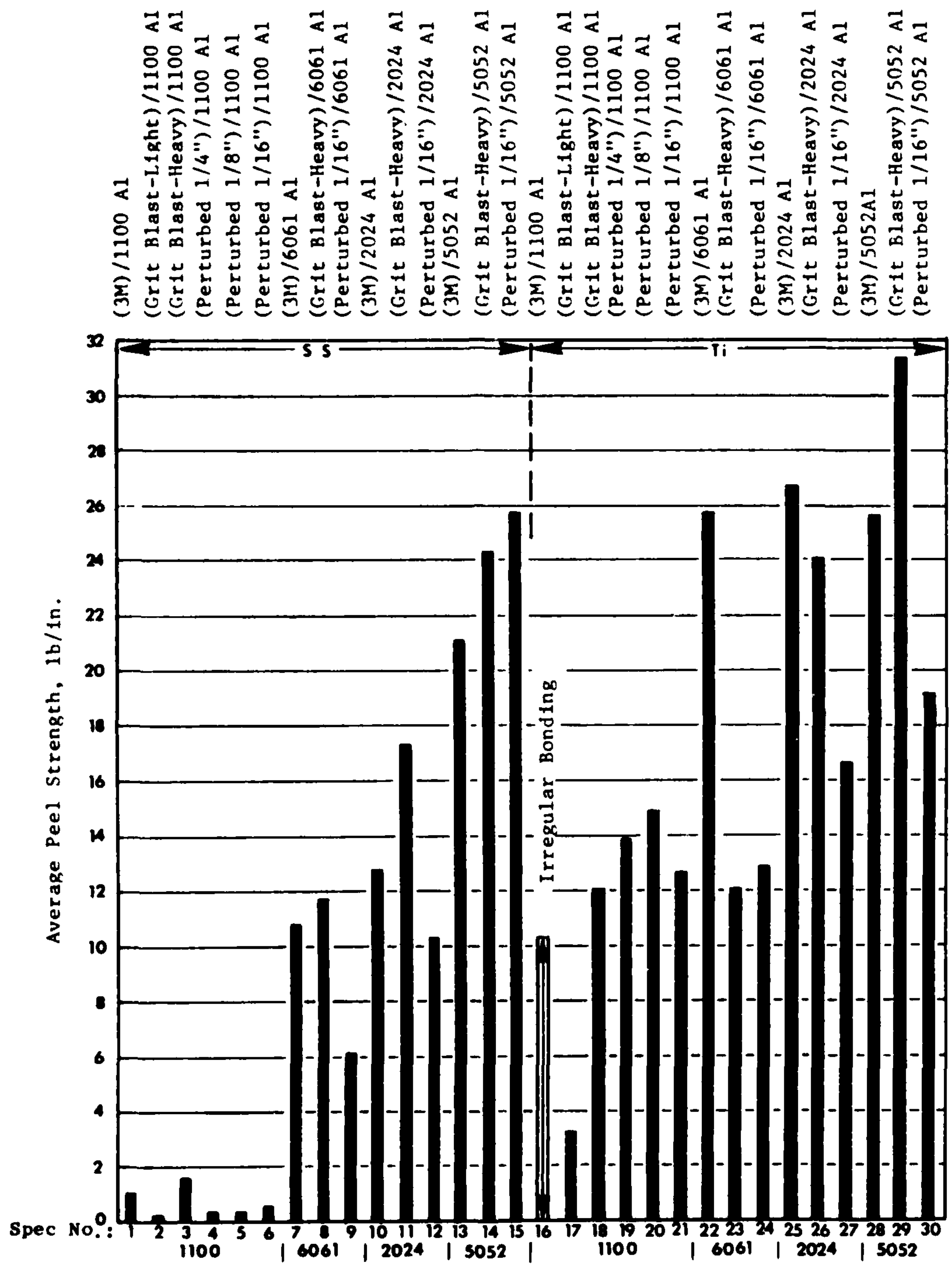

Figure 8. Peel Bond Strength of Thirty Bonded Hybrid Tapes.

Boron/Metal Monotapes

The peel test results were then applied to select matrix and filament. The bond between the plies is enhanced with the boron filaments between the aluminum foil layers since the filament surfaces aid in deforming the aluminum during the bonding operation. The investigation included effects of the special etchant (C/L B30), boron nitride (BN) surface coating of the B filament (on both 5.6 mils and 8.0 mils diameter B), bonding of 1100 Al with 2024 Al, 5052 Al, and 6061 Al, and two bonding temperatures, 875°F, and 900°F.

The special etch C/L B30 treatment was modified based on poor bond results previously reported. Since prior testing indicated that a residual etchant might have been entrapped in the surface pores generated by the removal of the Al_3Fe, the procedure for etching with the C/L B30 treatment was changed. After the C/L B30 etch, the foils were given a water rinse in the same manner as the S/F 9 treatment then to the cleaner, Ridoline No. 72, for 30 seconds at 140°F. Following this, the foils were water rinsed, given a fixant dip, and finally air dried.

Both 5.6 mil and 8.0 mil diameter boron filaments were coated with boron nitride by essentially the same procedure previously employed to vapor deposit unalloyed aluminum on the filament surfaces. First, the filaments were initially wound on an aluminum foil. The surface of a winding, three inches by seven inches, was then covered with another aluminum foil. After coating the ends with a stop-off cement, the center three inch by five inch region was cleaned and coated with a BN powder. From the BN coated sections, three inch by five inch bonded monotapes were formed.

In preparation of the hybrid monotapes, the boron was initially drum wound on 1100 Al, cover sheets of 2024 Al, 5052 Al, and 6061 Al alloy foils were secured over the windings, and hot-pressed to form three inch by five inch bonded monotapes.

In the vacuum bond cycle, two pressing temperatures of 875°F and 900°F were employed. The lower temperature was chosen since it represents the standard monotape bonding cycle; the 25°F higher temperature was selected to further enhance bonding.

The peel test results presented in Table 4 clearly show the significant effect of temperature on bonding. For example, comparing Specimen No. 9 pressed at 875°F with Specimen No. 14, pressed at 900°F shows that at 875°F, the peel strength is only 0.9 lbs/in., while at 900°F, the peel strength is 12.5 lbs/in. Further, it can be seen that at the higher temperature, the 3M-to-3M surface, the 3M-to-S/F 9 surface, and the 3M-to-special etch are nearly all equal. At the lower bond temperature, however, the 3M-to-3M surface has the lowest bond strength of the three, while the 3M-to-S/F 9 has the highest bond strength. Again, it can be observed that the special etch, C/L B30, yielded only one-half the bond strength of the surface with the 3M-to-S/F 9 treatment. Several attempts were made to modify this special etch treatment in the course of this study, hoping to produce a higher bond strength. These efforts, so far as we proceeded with them, were not fruitful.

Table 4. Bond Strength of Pressed Monotapes Containing Boron Filaments.

Specimen	Matrix Combination	Surface Treatment	Boron Filament Diameter (mils)	Boron Surface Treatment	Processing (°F/ksi/min)	Bond Strength (lb/in)
1	1100 Al (0.002") to 1100 Al (0.002")	3M Scarred / Standard SF 9	5.6	None	875/5/35	8.0
2	1100 Al (0.002") to 1100 Al (0.002")	3M Scarred / Special Etch (CLB-30) + Etch Clean	5.6	None	875/5/35	4.4
3	1100 Al (0.002") to 1100 Al (0.002")	3M Scarred / Standard SF 9	5.6	BN Coated	875/5/35	0.8
9	1100 Al (0.002") to 1100 Al (0.002")	3M Scarred / 3M Scarred	5.6	None	875/5/35	0.9
4	1100 Al (0.002") to 1100 Al (0.002")	3M Scarred / Standard SF 9	8.0 (9,3 Space)	BN Coated	875/5/35	0.5
5	1100 Al (0.0025") to 1100 Al (0.0025")	3M Scarred / Standard SF 9	5.6	None	875/5/35	2.3

Table 4. Bond Strengths of Pressed Monotapes Containing Boron Filaments (Concluded).

Specimen	Matrix Combination	Surface Treatment	Boron Filament Diameter (mils)	Boron Surface Treatment	Processing (°F/ksi/min)	Bond Strength (lb/in)
6	1100 Al (0.002") to 2024 Al (0.002")	Standard SF 9 / 3M Scarred	5.6	None	875/5/35	13.7
7	1100 Al (0.002") to 5052 Al (0.002")	Standard SF 9 / 3M Scarred	5.6	None	875/5/35	12.8
8	1100 Al (0.002") to 6061 Al (0.002")	Standard SF 9 / 3M Scarred	5.6	None	875/5/35	14.0
10	1100 Al (0.002") to 1100 Al (0.002")	3M / Standard SF 9	5.6	None	900/5/35	14.8
11	1100 Al (0.002") to 1100 Al (0.002")	3M / Special Etch (CLB-30) + Etchant Clean	5.6	None	900/5/35	15.4
14	1100 Al (0.002") to 1100 Al (0.002")	3M / 3M	5.6	None	900/5/35	12.5

The BN coating on both the 5.6 mil and 8 mil boron filament produced low bond strength of only 9.8 lb/in. and 0.5 lb/in., respectively, it is not certain why these low bond strengths were observed, since the aluminum foil mating surfaces were prepared with the 3M-to-S/F 9 treatments. Possibly, the BN coatings on the boron were smeared across the mating interface, thereby prohibiting formation of a good bond.

The hybrid systems of 1100 Al with 2024 Al, 5052 Al, and 6061 Al in all cases yield excellent bonding. Certainly this is not surprising since the Al to Al bond strengths as given in Table 2 were high.

An added, follow-on effort was performed to evaluate the bonding of aluminum alloys with two other matrix materials, unalloyed titanium foil and 316 stainless steel foil. From the previous results reported under Metal/Metal Monotapes, a series of bonded monotapes (BMT) were consolidated as listed in Table 5. The BMT's contained the 5.6 mil diameter boron filament between the two metal sheets (one the aluminum alloy and the other either the stainless steel or the titanium sheet). The bonding conditions ranged from 875°F/5 ksi/30 minutes to 950°F/5 ksi/30 minutes. These results led to the conclusion that poor and insufficient bonding could be achieved from these tape combinations and processing cycles. All poorly bonded areas were against either the stainless steel or the titanium sheets. These poor bond results required another BMT bond study iteration to achieve adequate monotape integrity.

After four individual bond study experiments, it was determined that consistent bonding could be achieved by inserting an alloy foil layer between the stainless steel of the titanium sheet and against the boron filament. Based on these successful results, a series of bonded monotapes were hot-pressed bonded at 925°F/5 ksi/30 minutes. The BMT tapes, as listed in Table 6 were determined to be well bonded as evident by metallographic examinations and peel testing. In all cases where peel testing was attempted, tear failures occurred through the Al alloy sheet. From this study, it was concluded that sufficient bond conditions could be obtained with the BMT containing the added foil layer between the B filament and the Ti or stainless steel foils.

Eight-Ply Panels

Based upon the results from the BMT studies, ten aluminum/aluminum eight-ply panels (two from each of the five selected systems) were fabricated from bonded monotapes. Four of the five systems contained alternate layers of 1100 Al against an alloy aluminum foil. The five selected systems all contained the 5.6 mil diameter boron filaments at 50 volume percent and aligned at 0° orientation. These specimens were: (1) the all 1100 Al, (2) the 1100 Al bonded to 6061 Al, (3) the 1100 Al bonded to 5052 Al, (4) the 1100 Al bonded to 2024 Al and (5) the 1100 Al again bonded to 2024 Al, but containing boron nitride coated boron filaments. A summary of the surface treatments and pressing condition are given in Table 7. These bonded monotapes after the S/F 9 surface treatment were then assembled and vacuum hot-pressed into eight-ply panels at 920°F/6 ksi/35 minutes. All consolidated panels were exceptionally well bonded. They were then sectioned into longitudinal and transverse test specimens.

Table 5. Bonded Monotape (BMT) Formed by Vacuum Hot Pressing.

PROCESSING	I.D.	FABRICATION	RESULTS
920°F/5 ksi/30 min.		Alloy(treatment)/B(space)/Alloy(treatment)	
	BSP-31	SS(GB)/1100(S/F 9)	Not very well bonded; Some areas not bonded.
	BSP-BMT1	SS(GB)/B(6.5)/1100(3M)	Not bonded.
	BSP-BMT2	SS(GB)/B(6.5)/1100(S/F 9)	Not bonded in areas.
	BSP-BMT3 (1)	SS(pert)/B(6.5)/1100(3M)	Bonded; sacrif. sheet not removeable.
	BSP-BMT6	Ti(GB)/B(6.5)/1100(3M)	Not bonded in areas.
	BSP-BMT7 (2)	Ti(pert)/B(6.5)/1100(3M)	Bonded; sacrif. sheet not removeable.
875°F/5 ksi/30 min.			
	BSP-BMT4	SS(GB)/B(6.5)/5052(3M)	Not bonded.
	BSP-BMT5	SS(pert)/B(6.5)/5052(3M)	Not bonded.
	BSP-BMT8	Ti(GB)/B(6.5)/6061(3M)	Not bonded.
	BSP-BMT9	Ti(pert)/B(6.5)/6061(3M)	Poorly and uncompletely bonded in areas.
	BSP-BMT10	Ti(3M)/B(6.5)/5052(3M)	Not bonded.
875°F/5 ksi/30 min.			
	BSP-BMT11	Ti(GB)/B(6.5)/5052(3M)	Not bonded.
	BSP-BMT14	Ti(GB)/B(7.2)/5052(3M)	Not bonded.
950°F/5 ksi/30 min.			
	BSP-BMT12	Ti(pert)/3(6.5)/5052(3M)	Not bonded in areas.
	BSP-BMT13	Ti(3M)/B(7.2)/5052(3M)	Not bonded in areas.
	BSP-BMT15	Ti(pert)/B(7.2)/5052(3M)	Some areas bonded.

(1) Stainless steel side perturbed 1/16" before stack-up of panel.
(2) Titanium side perturbed 1/16" before stack-up of panel.

Table 6. Bonded Monotapes (BMT) Formed by Vacuum Hot Pressing with Additional Al Alloy Foil Layer.

Press Conditions: 925 ± 10°F/5 ksi/3 minutes

BMT SPEC NO.	BMT PREVIOUS NO.	FABRICATION	PREVIOUS CONDITIONS	REMARKS	RESULTS
1	-	(1) Ti(pert)/$\frac{.002}{5052}$(3M)/B(7.2) 5052(3M)	None	SS T-50 sacrif.	Well bonded smooth surface
2	-	SS(3M)/$\frac{.001}{1100(3M)}$/B(6.5) 1100(3M)	None	Alodine sacrif.	Well bonded sacrif. peel easily
3	BSP-BMT 1	(2) SS(GB)/$\frac{.001}{1100(3M)}$/B(6.5) 1100(3M)	925°F/5 ksi/ 30 minutes	Alodine sacrif.	Well bonded sacrif. peel easily
4	BSP-BMT 1	SS(GB)/$\frac{.001}{1100(3M)}$/B(6.5) 1100(3M)	925°F/5 ksi/ 30 minutes	1100-1118 T-50 sacrif.	Well bonded
5	-	SS(GB)/$\frac{.001}{1100(3M)}$/B(6.5) 1100(3M)	None	(same as above)	Well bonded
6	-	SS(GB)/$\frac{.001}{2024(3M)}$/B(6.5) 1100(3M)	None	(same as above)	Well bonded
7	-	SS(GB)/$\frac{\text{reg. BMT \#66-10}}{1100(3M)}$/B(6.5) 1100(3M)	850°F/4.8 ksi /15 minutes	(same as above)	Bonded in ctr. section - both sides not bonded
8	-	SS(3M)/$\frac{.001}{1100(3M)}$/B(6.5) 1100(3M)	None	(same as above)	Well bonded
9	-	SS(3M)/$\frac{.001}{2024(3M)}$/B(6.5) 1100(3M)	None	(same as above)	Well bonded
10	BSP-BMT 6	Ti(GB)/$\frac{.001}{1100(3M)}$/B(6.5) 1100(3M)	925°F/5 ksi/ 30 minutes	(same as above)	Well bonded

(1) Titanium sheet perturbed 1/16" before stack-up of panel.
(2) Stainless steel sheet perturbed 1/16" before stack-up of panel.

Table 6. Bonded Monotapes (BMT) Formed by Vacuum Hot Pressing with Additional Al Alloy Foil Layer (Concluded).

Press Conditions: 925 ± 10°F/5 ksi/3 minutes

BMT SPEC NO.	BMT PREVIOUS NO.	FABRICATION	PREVIOUS CONDITIONS	REMARKS	RESULTS
11	-	Ti(GB)/.001 1100(3M)/B(6.5) 1100(3M)	None	(same as above)	Well bonded
12	BSP-BMT 6	Ti(GB)/.001 2024(3M)/B(6.5) 1100(3M)	925°F/5 ksi/ 30 minutes	(same as above)	Well bonded
13	BSP-BMT 11	Ti(GB)/.002 5052(3M)/B(6.5) 5052(3M)	875°F/5 ksi/ 30 minutes	(same as above)	Well bonded
14	BSP-BMT 10	Ti(3M)/.002 5052(3M)/B(6.5) 5052(3M)	875°F/5 ksi/ 30 minutes	(same as above)	Well bonded
15	BSP-BMT 10	Ti(3M)/.001 2024(3M)/B(6.5) 5052(3M)	875°F/5 ksi/ 30 minutes	(same as above)	Well bonded
16	BSP-BMT 14	Ti(3M)/.002 5052(3M)/B(7.2) 5052(3M)	875°F/5 ksi/ 30 minutes	(same as above)	Well bonded
17	BSP-BMT 14	Ti(GB)/.001 2024(3M)/B(22) 5052(3M)	875°F/5 ksi/ 30 minutes	(same as above)	Well bonded
18	-	Ti(GB)/.002 5052(3M)/B(6.5) 5052(3M)	None	(same as above)	Well bonded
19	-	Ti(GB)/.001 2024(3M)/B(6.5) 5052(3M)	None	(same as above)	Well bonded

Table 7. Aluminum/Aluminum Bonded Monotapes and Panels.

Select System	No. of Tapes	Alloy 0.002" Thickness	Surface Treatment	Boron Filament Parameter, mils	Press Conditions	Consolidated* Panel Number
I.	18	1100 to 1100	3M S/F9	5.6	900° F/5 ksi/35 min.	1 2
II.	18	1100 to 6061	S/F9 3M	5.6	875° F/5 ksi/35 min.	3 4
III.	18	1100 to 5052	S/F9 3M	5.6	875° F/5 ksi/35 min.	5 6
IV.	18	1100 to 2024	S/F9 3M	5.6	875° F/5 ksi/35 min.	7 8
V.	18	1100 to 2024	S/F9 3M	5.6 with BN Coating	875° F/5 ksi/35 min.	9 10

*Panels were consolidatd at 920° F/6 ksi/35 min. with the S/F interply surface treatment.

Select BMT were prepared with the 5.6 mil diameter boron filament between the titanium or stainless steel foils and the aluminum alloy foil hybrid composite sheets. These tapes were fabricated at 925°F/5 ksi/30 minutes. Following this pressing cycle, the bonded tapes were inspected, then grit blasted to prepare the mating surfaces. The prepared BMT's were acetone cleaned immediately prior to stacking and pressing into ten eight-ply panels at 950°F/6 ksi/15 minutes. In stacking, all filaments were aligned in 0^{o} orientation. Table 8 records the panel numbers along with the BMT's fabrication conditions. From these tapes, the eight-ply three inch by five inch panels were consolidated. These panels were then machined into miniature specimens 0.4 inch wide by 2.5 inch long with a nominal thickness of 0.07 inches.

Bend tests were conducted on the eight-ply panel specimens using a three-point test fixture capable of being mounted in an Instron testing machine. The crosshead rate of 0.05 center load was applied against the alloyed layer ply.

The aluminum/aluminum bend test results are presented in Table 9. The B/Al system which indicated the lowest longitudinal bend strength was the 1100 Al/1100Al with a calculated stress of 250 ksi. All the other four B/Al systems exhibited longitudinal bend strengths in the order of 310-320 ksi. The 2024 Al/1100 Al indicated the highest transverse bend strength in the order of 50 ksi, while the 1100 Al/1100 Al had the lowest of about 20 ksi.

Bend tests were similarly performed on the aluminum/titanium and aluminum/stainless steel hybrid composite specimens reinforced with boron filaments. These test results revealed calculated strengths in the order of 250 ksi for the 1100 Al/titanium eight-ply specimens and only about 200 psi for the 1100 Al/stainless steel specimens.

Unnotched pendulum impact tests were conducted on the eight-ply panels using a Physmet miniature impact tester, Model CIM-24, seen in Figure 9. The dimensions of the specimens were a nominal 2.5 inches long by 0.4 inches wide by 0.065 inches thick. Early impact results revealed the anisotropic behavior of these composites. When impacted against the alloy aluminum side, they exhibited nearly twice the energy absorption as that exhibited when hit against the 1100 Al side. Hence, in all impact testing the composites were struck on the aluminum alloy surface. An estimate was made of the full-size Charpy impact value by employing the following relationship:

$$E_c = \frac{0.250}{A} \cdot E_{mc}$$

where

E_c = full-size Charpy impact energy, ft-lbs

E_{mc} = miniature impact energy ft-lbs

A = cross-sectional area of the test specimens

Table 8. Panel Numbers and BMT Fabrication Conditions Used in Consolidating Eight-Ply Panels

PANEL NO.	BMT FABRICATION CONDITIONS	BMT PRESSED AT	PANEL PRESSED AT
BSP-8P1	SS(GB)/$\frac{.001}{1100(3M)}$/B(6.5)/1100(3M)	925°F+10°F/ 5 ksi/ 30 minutes	950°F/6 ksi/ 15 minutes
BSP-8P2	Ti(3M)/$\frac{.001}{1100(3M)}$/B(6.5)/5052(3M)	(same as above)	(same as above)
BSP-8P3	*Ti(3M)/$\frac{.001}{1100(3M)}$/B(6.5)/5052(3M)	(same as above)	(same as above)
BSP-8P4	Ti(GB)/$\frac{.001}{1100(3M)}$/B(6.5)/5052(3M)	(same as above)	(same as above)
BSP-8P5	Ti(3M)/$\frac{.001}{1100(3M)}$/B(7.2)/5052(3M)	(same as above)	(same as above)
BSP-8P6	**Ti(3M)/$\frac{.001}{1100(3M)}$/B(7.2)/5052(3M)	(same as above)	(same as above)
BSP-8P7	Ti(GB)/$\frac{.001}{1100(3M)}$/B(7.2)/5052(3M)	(same as above)	(same as above)
BSP-8P8	Ti(GB)/$\frac{.001}{1100(3M)}$/B(6.5)/1100(3M)	(same as above)	(same as above)
BSP-8P9	Ti(3M)/$\frac{.001}{1100(3M)}$/B(6.5)/1100(3M)	(same as above)	(same as above)
BSP-8P10	***Ti(3M)/$\frac{.001}{1100(3M)}$/B(6.5)/1100(3M)	(same as above)	(same as above)

* Plus Ti side perturbed 1/16" before stack-up of panel
** Plus mirror image, both outer surfaces are Ti
*** Plus Ti side, perturbed 1/16" before stack-up of panel

Table 9. Bend Test Results on the Aluminum/Aluminum 8-Ply Panels from the Five Select Systems.

$$\text{Strength} = \frac{3\,PL}{2bd^2}$$

Gage Length L = 1.5"

Material and Fabrication	Specimen No.	Thickness d, inch	Width b, inch	P, Pounds	Strength, ksi
8 Plies of 5.6B	BS-5061-2B-1L	0.065	0.318	150.0	250.0
All 1100 Al	-2B-2L	0.065	0.330	156.0	250.7
Intra and Inter S/F9	-2B-1T	0.065	0.298	11.6	20.9
	-2B-2T	0.065	0.335	12.9	20.7
8 Plies of 5.6B	BS-506(6/1)-3B-1L	0.063	0.298	174.0	326.3
6061/1100	-3B-2L	0.063	0.315	173.0	311.4
3M/S/F9 Intra	-3B-1T	0.063	0.286	15.8	30.9
S/F9 Inter	-3B-2T	0.063	0.295	18.6	34.9
8 Plies of 5.6B	BS-506(5/1)-5B-1L	0.064	0.308	172.0	309.6
5052/1100	-5B-2L	0.064	0.313	160.0	276.9
3M/S/F9 Intra	-5B-1T	0.064	0.280	17.2	33.7
S/F9 Inter	-5B-2T	0.064	0.322	17.4	30.1
8 Plies of 5.6B	BS-506(2/1)-8B-1L	0.064	0.286	169.0	330.7
2024/1100	-8B-2L	0.064	0.315	174.0	301.2
3M/S/F9 Intra	-8B-1T	0.064	0.280	24.5	47.9
S/F9 Inter	-8B-2T	0.064	0.283	26.0	50.9
8 Plies of 5.6B	BS-506BN(211)-10B-1L	0.065	0.313	179.0	309.8
B Fil. Coated with BN	-10B-2L	0.065	0.304	181.0	313.3
2024/1100	-10B-1T	0.065	0.283	22.7	42.6
3M/S/F9 Intra	-10B-2T	0.065	0.285	19.8	37.1
S/F9 Inter					

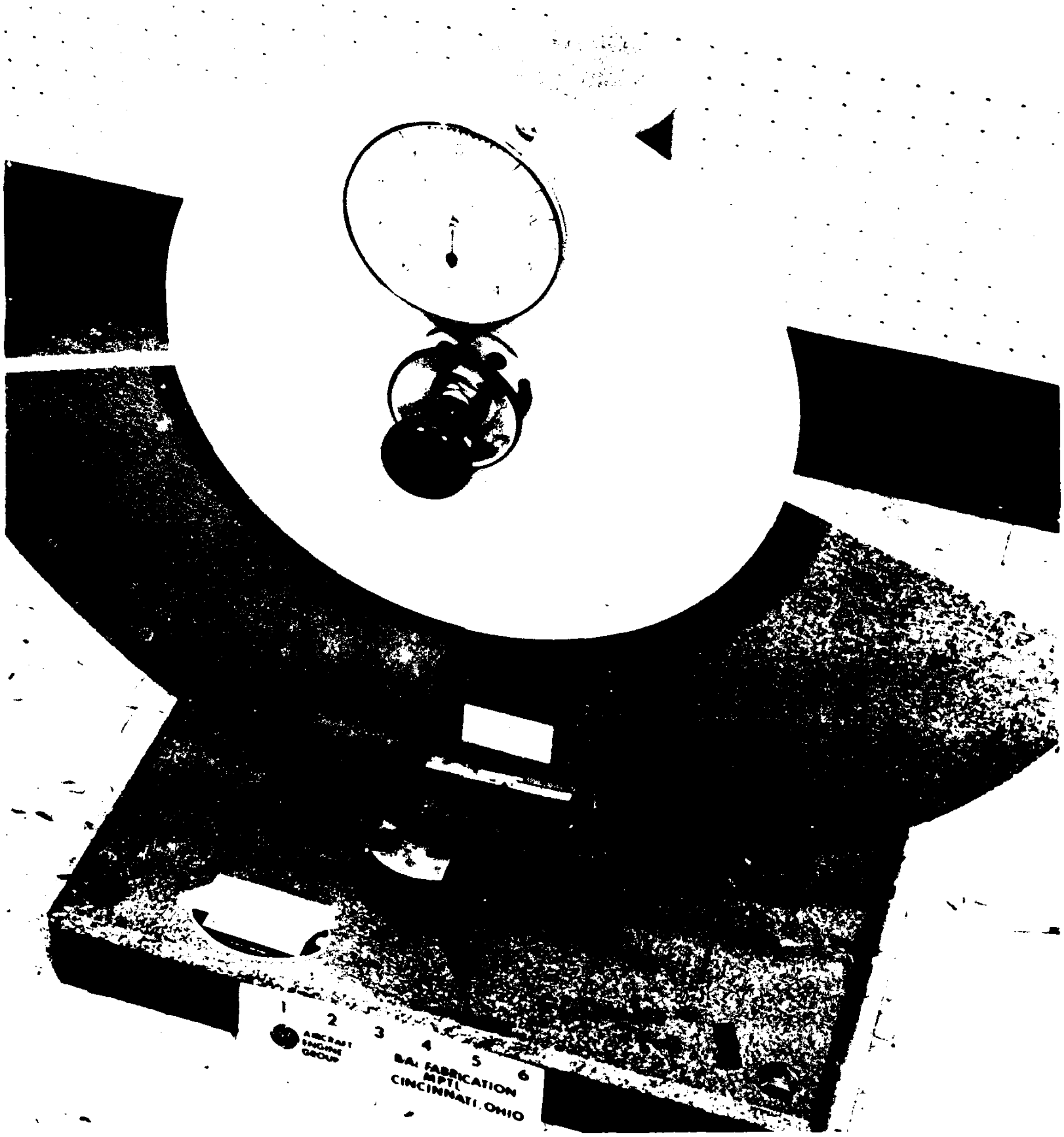

Figure 9. Physmet Impact Testing Machine for Impact Evaluation of Miniature Impact Specimens.

Table 10 records the test results on the eight-ply specimens. The impact system which has been identified to produce the highest longitudinal impact strength is the 1100 Al/1100 Al system. The corrected impact strength for this all-100 Al system was calculated to be nearly 22 ft-lbs. The impact strength of the 2024 Al/1100 Al system exhibited the lowest impact strength, calculated to be about 12.5 ft-lbs. Also noted was the all-1100 Al system showed the lowest transverse impact strength of only about 4.5 ft-lbs, while the 6061 Al/1100 Al produced the highest transverse strength with an average of greater than 10 ft-lbs.

Scanning electron microscopy (SEM) evaluation of the impacted surface revealed an interesting feature in fracture of these specimens. When impacted on the 2024 Al side, the impact strength was nearly twice that strength as when hit on the 1100 Al side. The SEM revealed that the 1100 Al-to-boron interface was more readily disassociated, while the fracture at the 2024 Al-to-boron interface was nearly flush across the fracture zone. This suggests that the 2024 Al bonds better to the boron and under the tensile loading as seen in the impact away from the impacting tup face, does not allow the aluminum to move and deform. Hence, less energy can be absorbed in this case. The converse is true when impacted against the 2024 Al side in that the 1100 Al-to-boron can more readily deform and, in this instance, more energy is dissipated.

These same five systems were fabricated into essentially full-size Charpy specimens containing fifty plies of monotapes and these were evaluated by instrumented Charpy impact testing.

Unnotched impact tests were also performed on the aluminum/titanium and aluminum/stainless steel hybrid composites. The results, shown in Figure 10, led to lower than anticipated impact strengths. The highest corrected impact strength of about 22 ft-lbs was evident with the titanium/1100 Al panel. It was also observed that the stainless steel/1100 Al panel yielded impact strengths in excess of 20 ft-lbs.

Since these values were not as high as anticipated, another eight-ply panel bonding iteration study was made. In this study, based on the high bond characteristics evident in the fractured surface, six additional eight-ply panels were formed on the two select systems of titanium/1100 Al and stainless steel/1100 Al. In this additional investigation, both lower BMT bond temperature as well as lower panel consolidation temperatures were used. A summary of the eight-ply panel numbers and BMT fabrication condition are listed in Table 11.

As before, miniature impact specimens were machined from the consolidated eight-ply panels. These machined specimens were impact tested as before and the results recorded in Table 12. One test on the stainless steel/1100 Al, 8P13, yielded anomalously high impact strength of 154 ft-lbs, but an additional specimen was prepared and impacted and found to have a more consistent impact strength. In an attempt to improve the impact strength, one specimen was given a vacuum heat treat at 750°F/30 minutes and again impacted. No significant difference was observed. In general then, the results were

Table 10. Impact Test Results on the 8-Ply Panels from the Five Select Systems.

$$\text{Impact Energy} = \text{ft-lbs} \times \frac{0.250}{\text{Area}}$$

Material and Fabrication	Specimen No.	Thickness, inch	Width, inch	Area, $inch^2$	Measured Energy, ft-lbs	Impact Energy, ft-lbs
8 Plies of 5.6B	BS-5061-2I-1L	0.065	0.419	0.0272	2.332	21.43
All 1100	-2I-2L	0.065	0.423	0.0275	2.400	21.82
Intra and Inter S/F9	-2I-1T	0.065	0.385	0.0250	0.382	3.82
	-2I-2T	0.065	0.403	0.0262	0.567	5.41
8 Plies of 5.6B	BS-506(6/1)-3I-1L	0.063	0.386	0.0243	1.499	15.42
6061/1100	-3I-2L	0.063	0.399	0.0251	1.550	15.44
3M/S/F9 Intra	-3I-1T	0.063	0.368	0.0232	0.835	9.00
S/F9 Inter	-3I-2T	0.063	0.375	0.0236	1.138	12.06
8 Plies of 5.6B	BS-506(5/1)-5I-1L	0.064	0.399	0.0255	1.691	16.58
5052/1100	-5I-2L	0.064	0.400	0.0256	1.603	15.65
3M/S/F9 Intra	-5I-1T	0.064	0.401	0.0257	0.602	5.86
S/F9 Inter	-5I-2T	0.064	0.405	0.0259	0.631	6.09
8 Plies of 5.6B	BS-506(2/1)-8I-1L	0.064	0.404	0.0259	1.230	11.87
2024/1100	-8I-2L	0.064	0.377	0.0241	1.248	12.95
3M/S/F9 Intra	-8I-1T	0.064	0.397	0.0254	0.649	6.39
S/F9 Inter	-8I-2T	0.064	0.374	0.0239	0.761	7.96
8 Plies of 5.6B	BS-506BN(2/1)-10I-1L	0.065	0.400	0.0260	1.512	14.54
B Fil. Coated with BN	-10I-2L	0.065	0.401	0.0261	1.445	13.84
2024/1100	-10I-1T	0.065	0.385	0.0250	0.532	5.32
3M/S/F9 Intra	-10I-2T	0.065	0.370	0.0241	0.680	7.05
S/F9 Intra						

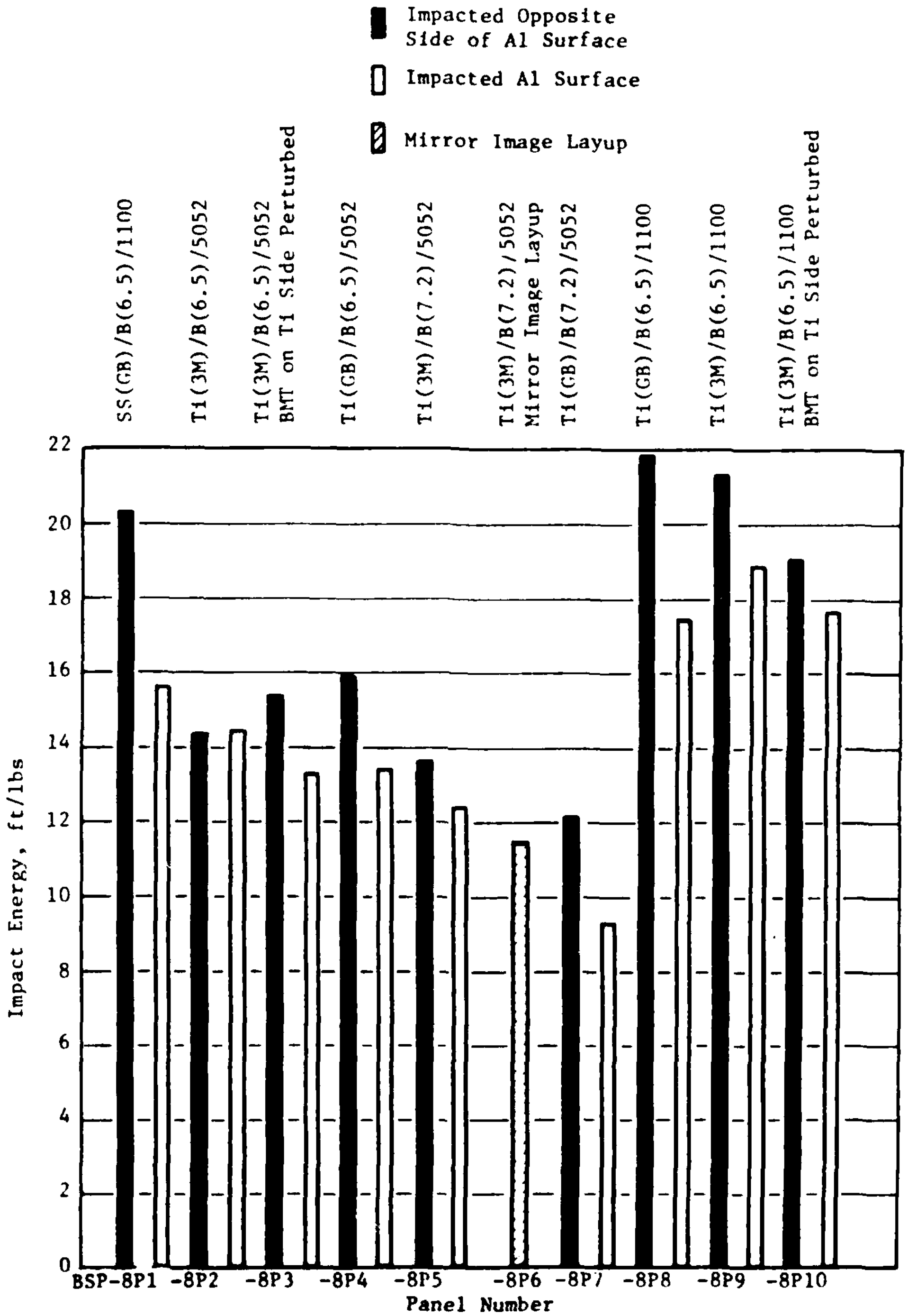

Figure 10. Miniature Impact Test Result on 8 Ply Aluminum/Titanium and Aluminum/Stainless Steel Hybrid Composite Panels Consolidated at 950° F/6 ksi/15 minutes.

Table 11. Panel Numbers Along With BMT and Panel Fabrication Conditions Used in Consolidating 2nd Series of Eight-Ply Panels

PANEL NO.	BMT PRESS CONDITION	PANEL PRESS CONDITION
BSP-8P11	SS/B/1100 Al 900°F/5 ksi/15 minutes	900°F/6 ksi/15 minutes
BSP-8P12	Ti/B/1100 Al 900°F/5 ksi/15 minutes	900°F/6 ksi/15 minutes
BSP-8P13	SS/B/1100 Al 900°F/5 ksi/15 minutes	925°F/6 ksi/15 minutes
BSP-8P14	Ti/B/1100 Al 900°F/5 ksi/15 minutes	925°F/6 ksi/15 minutes
BSP-8P15	Ti/B/1100 Al 900°F/5 ksi/15 minutes	925°F/6 ksi/15 minutes
BSP-8P16	Ti/B/1100 Al 900°F/5 ksi/15 minutes	925°F/6 ksi/15 minutes

Table 12. Miniature Impact Test Results on Eight-Ply Panels

Bond Study Program
Impact Specimens

Spec. Size: 0.4" W x 2.5" L x 8-Ply T (5.6 B Dia.-0°)
Impacted on SS or Ti Side Impact Energy = Ft-Lbs x $\frac{250}{\text{Area}}$

PANEL NO. & FABRICATION		SPEC NO.	THK.	SPEC. DIM. WIDTH	AREA	FT-LBS	IMPACT ENERGY FT-LBS	AVERAGE
BSP-8P11								
SS/B/1100 Al								
Panel-900°F/6 ksi/15		11-3L	.0694	.388	.027	1.94	17.96	
BMT-900°F/5 ksi/15		11-4L	.0690	.388	.027	1.93	17.87	17.92
BSP-8P12								
Ti/B/1100 Al		12-3L	.0729	.382	.028	4.12	36.79	
Panel-900°F/6 ksi/15		12-4L	.0710	.403	.029	2.44	21.03	
BMT-900°F/5 ksi/15		12-2L	.0708	.411	.029	2.43	20.95	26.26
BSP-8P13		13-3L	.0738	.400	.030	18.58	154.83	
SS/B/1100 Al		13-4L	.0718	.399	.029	2.04	17.59	
Panel-925°F/6 ksi/15		13-1L	.0730	.408	.030	1.35	11.25	
BMT-900°F/5 ksi/15		13-2L	.0720	.389	.028	1.84	16.43	15.09
BSP-8P14		14-3L	.0715	.403	.029	3.10	26.72	
Ti/B/1100 Al		14-4L	.0713	.379	.027	2.56	23.70	
Panel-925°F/6 ksi/15		14-1L	.0705	.358	.025	2.11	21.10	
BMT-900°F/5 ksi/15		14-2L	.0710	.379	.027	2.50	23.15	23.67
							(Vac. Heat Treat at 750°F/30 min.)	
BSP-8P15								
Ti/B/1100 Al		15-3L	.0738	.381	.028	3.66	32.68	
Panel-925°F/5 ksi/15		15-4L	.0740	.386	.028	2.62	23.39	
BMT-900°F/5 ksi/15		15-2L	.0738	.418	.031	2.77	22.34	26.14
BSP-8P16		16-3L	.0729	.386	.028	2.73	24.37	
Ti/B/1100 Al		16-4L	.0730	.375	.028	3.01	27.87	
Panel-925°F/4 ksi/15								
Inner Ply perturbed								
BMT-900°F/5 ksi/15								26.12
Standards 6061 Al	Before	1	.0628	.409	.026	5.95	57.21	
		2	.0631	.373	.024	5.29	55.10	56.16
	After	3	.0628	.376	.024	5.09	53.02	
		4	.0628	.400	.025	5.62	56.20	54.61

somewhat discouraging in that, under the variables investigated, no significant impact strength improvement was evident.

Instrumented Charpy Impact Testing

To obtain a correlation between the miniature impact specimens and full-size Charpy specimens, all five aluminum/aluminum systems were selected for Charpy impact evaluation. In this effort, five panels, each containing fifty bonded monotape plies were stack and vacuum hot-press consolidated at 920°F/6 ksi/35 minutes. Table 13 records the thickness of these panels after consolidation. All panels were shipped to the vendor and finished machined into unnotched Charpy impact specimens. After the machined specimens were received, they were visually inspected, measured and subjected to the Charpy impact testing using the instrumented procedures described below.

Instrumented impact testing was made possible by the substitution of a specially instrumented tup for the standard tup within the machine hammer assembly as seen in Figure 11. The Dynatup loading tup and associated electronics were from Effects Technology, Inc., through the Tinius-Olsen Company. With the appropriate instrumentation, the strain gages located in the tup permitted measurement of the instantaneous load-time and energy-time tup responses resulting from impact with the specimens during testing. The strain gage output is monitored on an oscilloscope producing a load-time trace, which then is later photographed. A block diagram of the instrumentation is shown in Figure 12. The pendulum with the 50° setting provided an impact velocity of 101.97 in./sec.

The test results are recorded in Table 14. In comparison of the Physmet impact energies with the instrumented impact energy it can be noted that they rank in the same order; however, in all cases the Physmet energies are higher. This may be explained on the basis that the Physmet velocity is about only 20% that of the Tinius-Olsen impact machine. The impact energy is highest for the all-1100 Al system while it is lowest for the 1100 Al/2024 Al system. Another interesting observation on the miniature specimen is that the maximum load for all five systems are essentially the same, i.e., about 200 lbs. However, comparison of the oscilloscope photographs reveal that the all-1100 Al system displays a broader load-time trace compared with the 1100 Al/2024 Al system, and the all-1100 Al indicating nearly double the area under the curve.

The full-size Charpy specimen impact results show the all-1100 Al system to have the highest impact energy of 17 ft-lbs, with the 2024 Al/1100 Al hybrid systems with the lowest impact energy of only 7 ft-lbs. Although this is the highest level of energy on the all-1100 Al system, it is considerably lower than a value of nearly 50 ft-lbs previously observed. In the current studies, this all-1100 Al system was well bonded while the previous results revealed extensive delaminations. The load-time trace of the all-1100 Al system displays the lowest maximum load of 1800 lbs, while the BN coated, 2024 Al/1100 Al system has the highest value of 2800 lbs. The load-time trace for the all-1100 Al demonstrates considerably larger area under the curve, thereby allowing inter- and intralaminar shear to occur and dissipating larger quantities of energy.

Table 13. Thickness (Inch) of Consolidated Panels for Task IV.

Panel Material	End	Center	End	Average
50 Plies of 5.6B All 1100 Al	0.344	0.344	0.352	0.348
50 Plies of 5.6B 6061 Al/1100 Al	0.363	0.360	0.354	0.359
50 Plies of 5.6B m5052 Al/1100 Al	0.352	0.360	0.358	0.356
50 Plies of 5.6B 2024 Al/1100 Al	0.366	0.368	0.370	0.368
50 Plies of 5.6B Coated with BN 2024 Al/1100 Al	0.363	0.363	0.362	0.363

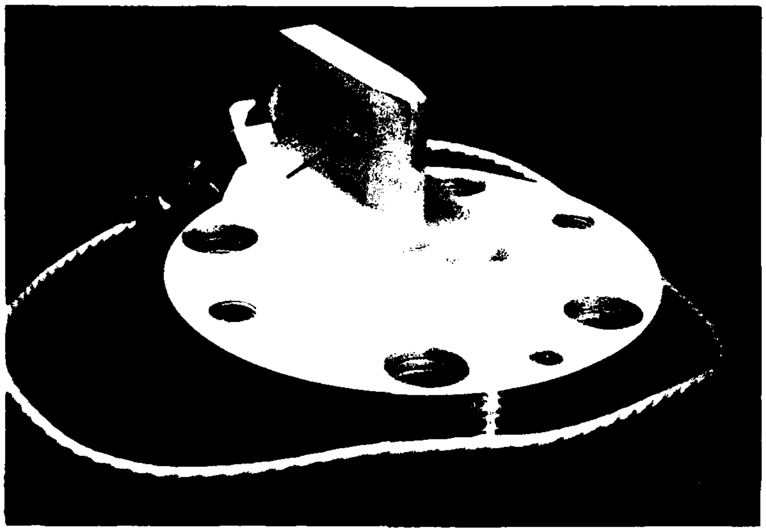

Figure 11. Photgraph of Instrumented Tup (Base is 4 in. Diameter).

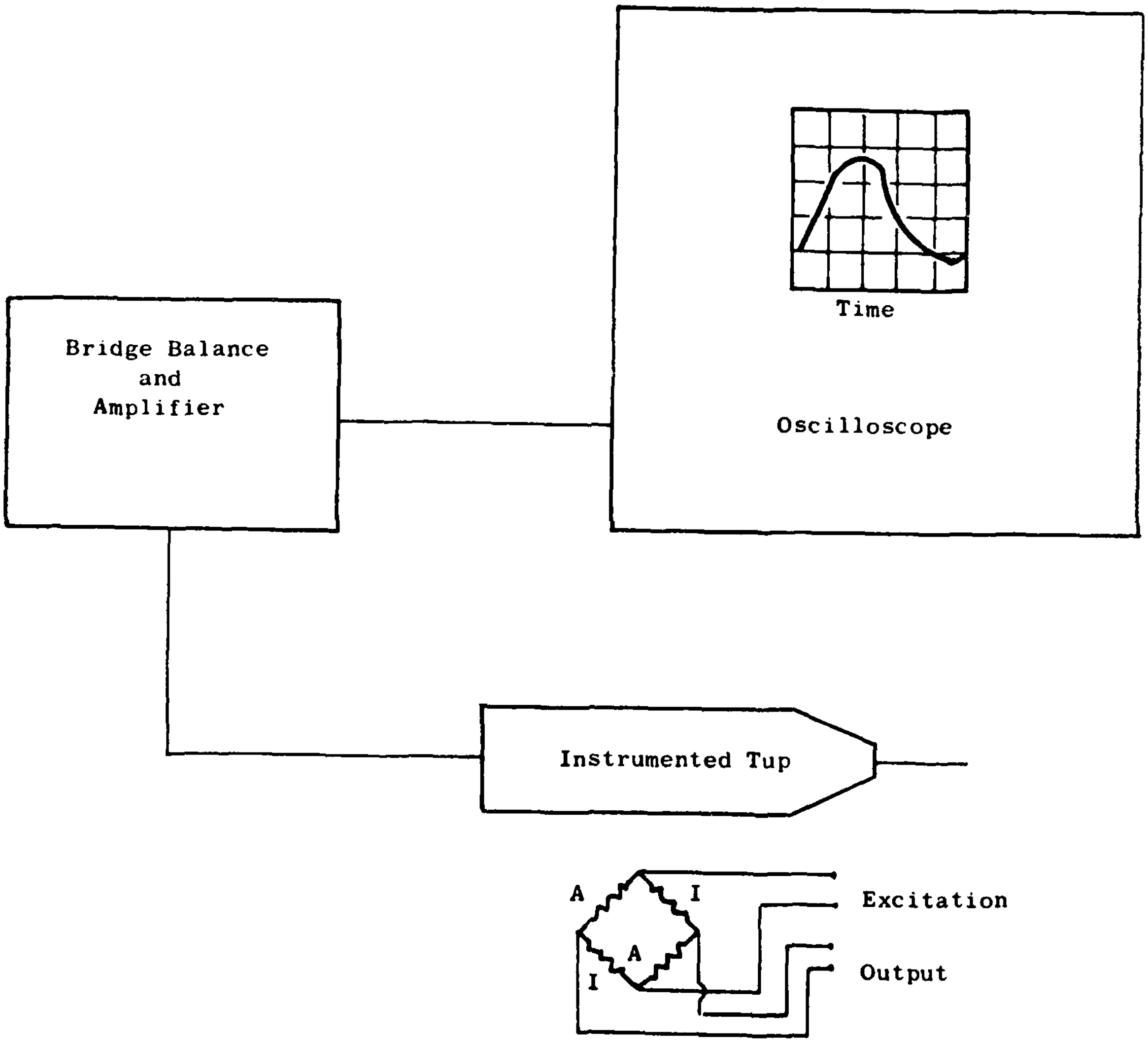

Figure 12. Schematic of Test Equipment for Instrumented Charpy Impact Testing.

Table 14. Instrumented Charpy Test Results Along with Physmet Impact Results.

System	B Filament	Filament Direction	Physmet Miniature Energy, ft/lbs		Instrumented Miniature, Charpy		Instrumented Full-Size Charpy	
			Measured	Converted	Energy, ft-lbs	Maximum Load, lbs	Energy, ft-lbs	Maximum Load, lbs
1100/1100	5.6 Uncoated	Long	2.37	21.60	1.50	200	17.0	1800
6061/1100	5.6 Uncoated	Long	1.52	15.43	---	210	9.5	2200
5052/1100	5.6 Uncoated	Long	1.66	16.12	1.10	210	8.5	2200
2024/1100	5.6 Uncoated	Long	1.24	12.42	0.75	200	7.0	2480
2024/1100	5.6 BN Coat	Long	1.48	14.19	1.15	200	7.0	2800

CONCLUSIONS

Initial studies on the mechanical surface preparation of aluminum alloy sheets indicate that an intermediate 3M surface abrasion gave the best overall bond behavior. From chemical surface preparation, it was determined that an in-house developed surface treatment, designated S/F 9, produced the highest bonding levels. However, this surface treatment delineated surface particles identified to be Al_3Fe on the 1100 Al. From experimental investigations, a special chemical surface treatment (94% H_2O, 5.5% HNO_3, 0.5% Hf) has been identified which completely removes these Al_3Fe particles. Although these Al_3Fe particles are etched away, an unknown residual agent is left behind which still inhibits bonding. However, the mechanism to improve interply bonding is still valid and suitable optimization of bonding conditions should lead to metal matrix exhibiting higher impact behavior. Peel tests on specimens of 1100 Al bonded to 2024 Al reveal excellent bonding.

In boron filament surface preparation, the standard trichloroethane cleaning produced best bonding of the surface systems considered.

The highest hybrid bond strength can be achieved with the 5052 Al alloy against either titanium or stainless steel foils. Bond strengths of the 5052 Al bonded to titanium are five to ten times greater than those of the 5052 Al bonded to the stainless steel.

Fabrication processes of aluminum/aluminum bonded monotapes, reinforced with the boron filament are very temperature sensitive. For example, an increase in temperature of only 25°F, from 875°F to 900° increases bond strengths by an order of magnitude. This 25°F increase has been found to produce exceptional bonding even for the 1100 Al to 1100 Al composite with only the 3M surface preparation. Initial fabrication of hybrid bonded monotapes led to only poor and insufficient bonding on the titanium/aluminum/boron (TAB) and the stainless steel/aluminum/boron (SAB) systems. This poor bonding necessitated the insertion of an intermediate aluminum layer between the titanium or stainless steel and the boron filament which led to high integrity bonded monotapes.

From bend test results on eight-ply panels containing 50 v/o B filaments at 0° orientation, revealed that the all-1100 Al matrix exhibited the lowest longitudinal and transverse strengths of respectively 250 ksi, and 20 ksi. The four 1100 Al/aluminum alloy systems consisting of alternate plies of 1100 Al and the alloy aluminum exhibited longitudinal strengths in the order of 310-320 ksi. The 2024 Al/1100 Al system had the highest transverse strength of 50 ksi. Bend tests performed on the TAB and SAB composites show strengths respectively of 250 ksi, and 200 ksi.

Impact tests on the eight-ply panel composite specimens of the all-1100 Al reveal them to possess the highest longitudinal impact strength of about 22 ft-lbs and the lowest transverse impact strength of only about 4 ft-lbs. From SEM observations, the filament-matrix bond with the 1100 Al matrix is considerably less than with the other alloy aluminum matrices, and as a result, the mode of energy release at the boron-1100 Al interface lead to greater energy dissipation. The miniature impact test results on the TAB and SAB hybrid components are somewhat discouraging in that under all variables investigated, no significant impact strength improvement was evident. The full-size Charpy specimens with the all-1100 Al, as with the eight-ply panel specimens, had the highest impact energy of 17 ft-lbs. Further, the full-size Charpy specimens with the 2024 Al/1100 Al composite had the lowest impact energy of only 7 ft-lbs. These results suggest that higher impact energies could be achieved with lower inter- and intraply bonding.

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