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FINAL REPORT

"Evaluation of Forming and Manufacturing Characteristics of Boron/Aluminum Materials"

NAS8-29081

J. F. Dolowy, Jr.

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Abstract

Low cost techniques were evaluated for forming boron-reinforced aluminum structural shapes from diffusion-bonded flat sheet and plate. Successful forming was accomplished on fully consolidated material up to .46 cm (0.180") thick. Five hat sections 12" long were formed from .25 cm (0.100") thick flat plates 12" long by 7" wide. Three of the hat sections were tested in cyclic compression to demonstrate the performance capability of structures by this type of low-cost secondary fabrication. The structural efficiency of these hats was found to be equal or superior to similar structures fabricated by more costly techniques.

"Evaluation of Forming and Manufacturing Characteristics
of Boron/Aluminum Materials"

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I. INTRODUCTION

Boron-reinforced aluminum composite material is no longer a laboratory curiosity. It is routinely produced in relatively large quantities and large sizes in the form of monolayer tape, multilayer sheet and plate, and complex die-formed structures by hot press diffusion-bonding. Further, the price of this versatile engineering material has dropped steadily and promises to continue this decrease as quantity usage increases. The high quality, producibility, and performance capability of diffusion-bonded boron-aluminum composites has been demonstrated in a number of highly successful and complex structural applications. Boron-aluminum composite has outstanding longitudinal tension and compression properties, excellent transverse and shear strength, excellent fatigue properties, and is useful to 589K (600°F). It can be formed and joined in a variety of waysinto structural components. The major drawback to more widespread utilization of this material is cost: both basic material cost and the cost of fabricating finished structure. Considerable progress is being made and will continue to be made in the basic material cost. The primary intent of this study therefore, was to provide preliminary data on the feasibility of reducing secondary fabrication costs. The approach is based upon post-consolidation forming of diffusion-bonded boron-aluminum plate, with the emphasis on relatively thick > 0.127 cm (> 0.050") flat plate.

Successful forming from flat plate could result in a very favorable cost picture, since the premium for forming would be only a small percentage increase over the basic plate cost.

II. DISCUSSION

A. Preliminary Bending Studies

The preliminary bending studies were conducted on uniaxially reinforced composite specimens of several thicknesses, with and without cladding, and with several variations in back-up method used. These studies were conducted over a range of temperatures to determine workable parameters and tooling for the subsequent forming of hat sections from thick B-Al composite sheet.

Specimen Preparation: Although the objective of the program was to evaluate low-cost methods of forming thick > .127 cm (.050") Al-B sheet and plate into structural shapes, a thinner-gauge material 0.076 cm (0.030") was used to provide a baseline. Several panels approximately 20 cm by 25 cm (8" by 10") were fabricated in thicknesses of 0.076 cm, 0.254 cm, and 0.457 cm (0.030", 0.10" and 0.18") by hot-press diffusion bonding 40 - 50 v/o 5.6 mil B in 6061 Al using standard Amercom processing procedures. The panels were all unidirectional orientation, with one panel of each thickness having a plain aluminum surface, one each with stainless-steel mesh bonded to each surface, and one each with both stainless-steel mesh and 0.102 cm (0.040") thick steel sheet bonded to each surface. These panels were then cut into bend-test specimens 5.08 cm by 15.2 cm (2" x 6").

Tooling: The tooling utilized consisted of a conventional power-bend brake with several configurations of male and female dies for forming the 90° bends. The female dies used included a 1.25 cm deep by 2.54 cm wide (1/2" x 1") 'V' groove die, a channel die 1.9 cm wide by 2.54 cm deep (3/4" x 1"), and a channel die 3.18 cm wide by 2.54 cm deep (1-1/4" by 1"). The male tools used included offset dies 0.51 cm and 0.89 cm diameter (0.20" and 0.35"; straight rod dies 0.95 cm, 1.27 cm, 1.58 cm and 1.9 cm diameter (3/8", 1/2", 5/8" and 3/4"), and a 1.27 cm diameter (1/2") rod offset die used to form the hat sections. Initially, radiant heaters were installed to supply heat to the tooling and workpiece. However, a maximum temperature of only 421°K (~300°F) could be reached in this manner. The mass of the dies and the complexity of insulating these from the basic machine have suggested a conduction rather than just a radiant heater. Several vendors and contacts who work in conventional metal fabrication were consulted and the general consensus was to use a Cal-Rod type heater. Two Cal-Rod heaters have been mechanically attached to the female tool and an initial calibration showed temperatures of approximately 505°K (450°F).

Several efforts were made to insulate the heated tools from the basic machine structure with transite board, and conventional spun insulation; however, the alignment and fit of the tools was affected. The most successful approach was to use woven asbestos cloth as a thin barrier. To reach temperatures greater than 533°K (500°F) and up to ~730°K (850°F), an oxy-acetylene torch was used. Temperature measurements were made using Tempilstiks smeared on the part as it was heated; however, initial temperature verification runs were carried out using both thermocouples and Tempilstiks.

Bend Test Results: Initial bend experiments with the 0.076 cm (0.030") thick composite demonstrated that good 90° bends could be produced at both slow and fast bending rates at temperatures below 366°K (200°F) for both mesh and mesh-plus-clad specimens, Table I. Some difficulty was experienced with unclad material at the low temperature, but this could be related to tooling problems, rather than an inherent limitation. The unclad, as well as the clad material could be successfully formed at 478°K (400°F). In these tests, 0.152 cm (0.060") thick aluminum back-up sheets were used. In addition, when a 0.038 cm (0.015") thick steel cover sheet was used, there was a noticeable improvement. The successful initial evaluations on the 0.076 cm (0.030") material were repeated, and several small angles and a 'Z' were formed. The effect of the thin-steel cover sheet again appeared to be very beneficial. It was evident from these tests that material up to 0.076 cm (0.030") thick can be successfully formed at low temperature and probably at room temperature with improved tool design. The stainless-steel mesh surfaces appeared to improve the bending reliability, as did the mesh-plus-clad surfaces.

All of the remaining bend studies involved the 0.254 cm (0.10") and thicker material, Table II. Attempts to duplicate the results obtained with the thin 0.076 cm material were unsuccessful in that bends greater than 45° in the .254 cm (0.10") thick material could not be achieved at the lower temperatures, 478°K (400°F) without cracking. Consequently, subsequent bending was conducted at temperatures in the 589°K to 700°K (600°F to 800°F) range. Invariably, bends made below 645°K (700°F) cracked, whereas bends made above 645°K did not. Successful bends were made at 645°K and above on both 0.254 cm and 0.46 cm (0.10" and 0.18") material using the 0.95 cm, 1.27 cm, and 1.58 cm (3/8", 1/2" & 5/8") diameter male tools in the 3.18 cm (1-1/4") wide channel die. However, the larger the male tool used in relation to a fixed female tool width, the higher the temperature necessary to make a successful bend. This higher temperature also results in more composite distortion and indentation which is undesirable. Therefore, to make acceptable bends with the larger male tool, it is necessary to increase the channel width. During this series of tests, several types of "back-up" methods were evaluated including: no back-up; 0.038 cm (0.015") steel sheet under the composite; 0.038 cm steel both sides; 0.038 cm and 0.16 cm (0.15" and 0.063") bottom with 0.038 cm cover sheet; and 0.038 cm steel plus 0.16 cm (0.063") aluminum between the composite and female die. The technique which appeared most effective used the 0.16 cm aluminum below the composite and the 0.038 cm steel between the aluminum and the female die. The apparent reason for the improvement with this combination is the adherence between the aluminum and composite at the high temperature, which must have been sufficient to shift the neutral axis toward the outer tension layers of the composite.

During the initial evaluations on 0.076 cm and 0.25 cm (0.030" and 0.10") B-Al composites, it appeared that no effects could be tied to the bend rate. The equipment used gave a "fast" rate of complete deformation in approximately 1/5 of a second; however, by not utilizing the inertia flywheel feature of this brake press, a slow bend rate of up to ~30 sec. could be achieved. This was done by utilizing

TABLE I INITIAL BEND SEQUENCE

Male Die $\sim$.35" Diam.; Female width $\sim$.70"

No.	Bend Rate	(cm) Composite "	Clad	(cm) Back-Up"	(°K) Temp. °F	Appearance	Comments
2229P-1	Slow	(.076cm) .030	No	(.152cm) .060 Al	200°F(366°K)	cracking	5 I B-Al only
	Fast				$\sim$200	cracking	
	Fast				400°F (478°K)	minor cracking	
2228P-1	Slow	.030	Mesh only	.060 Al	$\sim$200	cracking	
	Slow				$\sim$400	minor cracking	
	Fast				$\sim$200	very minor crack	(.037cm)
	Fast				$\sim$400	no cracks	.015 steel top sheet
2228P-2	Slow	.030	Mesh only	.060 Al	$\sim$400	cracking	(.037cm)
	Slow					no cracks	.015 steel top sheet
2227P-1	Slow	.030	Mesh & Steel	.060 Al	$\sim$200	no cracks	90° bend
	Slow				$\sim$400	no cracks	100° bend
	Fast				$\sim$200		Still clad with steel
2230P-2	Slow	(.254cm) .100	Mesh & Steel	.060 Al	350 (450°K)	@45°bend no cracks;	@90° fully split
	Fast	.100	Mesh & Steel	.060 Al	$\sim$400	cracked, also composite moved away from back-up sheet.	.037 cm steel top sheet
	Fast	.100	Mesh & Steel		$\sim$400	cracked	Graphite on tool
2230P-1	Slow	.100	Mesh & Steel	.060 Al	$\sim$400°F	cracked	.037cm steel top sheet

TABLE II - COMPOSITE FORMING

Male Die = .35" Diam.; Female Width = 1.25"

No.	Bend Rate	Composite Thickn. CM(in)	Surface Treatm.	Back-Up	Top Cover	Temp. °K (°F)	Appearance	Comments
1	Fast	.25cm	Mesh/Steel	.06 Al	-----	500°K	Cracked	Bent Beyond 90°
2	"	(.10)	"	"	-----	(450°F)	Cracked	Ruff Sheared Edge Started Crack
3	"	"	"	.06 Al+.015STL	-----	"	Slight Crack	"
4	"	"	"	.06Al+.065STL	-----	"	Cracked	
5	Slow	.46cm	"	.065STL	-----	"	"	
6	Fast	(.180")	"	"	.015 STL	"	"	
7	"	"	"	.06 Al	.065 STL	"	"	
8	"	.25cm	"	.015Al	.015 STL	"	Cracked	Cracks Start At ~40° Bend
9	"	"	"	.120 Al	.06Al	"	Cracked	"
10	"	.46cm	"	.06Al+.015STL	.015 STL	"	Cracked	"
11	"	"	"	" "	"	645°K	Partial Crack	Crack Started at Ruff Sheared Edge
12	"	"	"	" "		(700°F)	No Crack	~75°B, Minor Tool Indent
13	"	.25cm	"	.015 STL		"	" "	" " " "
16	"	.25	"	.015 STL	.06Al+.015S	645°K	Partial Crack	85° ∡ Tool Indented
17	"	.46	"	.065 STL	.065 STL	>645°K	No Cracks	Too Hot - Tool Indented
18	"	.46	"	"	"	645	" "	
19	"	.25	"	"	"	645	" "	
20	"	.25	"	"	"	>645	" "	
14	"	.46	"	.015 STL	-----	645	" "	Approx. 25°B With Fibers Running
15	"	.46	"	" "	-----	645	" "	Around The Formed Bend. No Apparent Fiber Breakage

Table II- Composite Forming (continued)

Female Width: 1.25"

No.	Bend Rate	Composite Thickness cm (in.)	Surface Treat-ment	Back-up	Top Cover	Tempera-ture, °F	Appearance	Male Die, in.	Comments
21	Fast	.25	mesh/steel	.065 stl	.065 stl	> 700	melted	1/2	Top .065 steel indented; some Al melt.
22	"	(.100)	"	"	"	"	no cracks	1/2	" " " minor indenting
23	"	.50	"	2 @ .065 stl	"	"	melted	"	Top steel indented; Al melt
24	"	(.200)	"	"	"	"	no cracks	"	" " " > 90°
25	"	.25	"	.065 stl	-	> 600	cracked	"	<90°
26	"	"	"	"	-	> 600	"	"	<90°
27	Slow	"	"	"	-	> 700	no cracks	"	~ 90°
28	"	.46	"	"	-	> 700	"	"	Indented top steel
29	"	.25	"	"	-	> 600	cracked	"	Slight top steel indentation
30	"	"	"	"	-	> 600	"	"	---
31	"	.46	"	"	-	> 700	no crack	"	<90°
32	"	.25	"	.080 Al + .065 Stl	-	> 600	cracked	"	-- > 90°
33	"	"	"	.065 stl	.080 Al	> 600	"	"	-- > 90°
34	"	"	"	.080 Al	.080 Al	"	"	"	<90°
35	"	"	"	.065 stl	.015 stl	"	"	"	composite not aligned
36	"	"	"	"	"	"	"	"	< 90°
37	"	"	"	.080 Al	"	"	"	"	<90°
38	"	"	"	.065 stl	-	<400	"	"	<90°
39	"	"	"	"	-	<400	"	"	<90°
40	"	"	"	"	.080 Al	<400	"	5/8	<90°

a slip clutch to walk the male die against the composite part and apply a small load; then, by easing off the clutch the load would hold (or slightly relax) until the clutch was re-engaged to apply the next small increment of load, etc.

Because of the "operator effect" on the slow bend rate, and since no effects of deformation rate within these limits were noted, all subsequent forming (#27 on) was done by setting the die initially onto the heated pack and applying a small load; then after checking alignment and temperature, the parts were formed in one or two incremental loadings, taking, typically, one to two seconds to apply.

Approximately 15 specimens of material thicker than 0.25 cm (0.10") were formed during the preliminary stages of this program. Although about half the specimens showed no tensile surface cracks, several other problems existed. The 0.46 cm (0.18") material, when heated to $\sim 660^{\circ}$K ($\sim 700^{\circ}$ to 800°F) had a pronounced tendency to be indented by the male and female tools during bending. This problem persisted through minor tooling and back-up material changes. In addition, close examination of the specimen edges paralleling the fiber direction showed a significant amount of shearing taking place which, in a real part, could create bulges adjacent to the formed corners as well as internally delaminated areas, which would markedly decrease compressive efficiency. Because of these effects, it is felt that B-Al uniaxial composites in thicknesses exceeding ~ 0.3 cm (0.10" to 0.15") may not be efficiently formed by the techniques used on this program, and further effort is needed to define acceptable parameters and tooling for thicker material.

B. Test Hat Fabrication

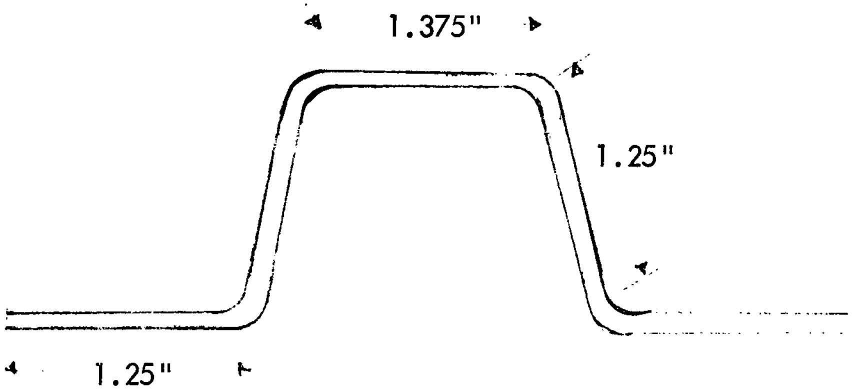
Based on the forming parameters derived in the bending experiments, hat-stiffener shapes, each approximately 30 cm (12") long were fabricated from 0.254 cm (0.10") composite material to demonstrate the effectiveness of low-cost forming of structural shapes from thick plate material. The design for the hat stiffeners was based upon similar hat stiffeners utilized by Convair and McDonnell Douglas on recent NASA structures programs to provide reasonably direct correlation of results with data generated on these other programs. Figure 1 shows a comparison of hat stiffeners.

Material Preparation and Tooling: A series of 45^{v}/o B-Al panels 30 cm x 17.8 cm x 0.254 cm (12" x 7" x 0.1") thick were fabricated with three surface conditions: stainless-steel mesh bonded to each surface; mesh and 0.1 cm (0.040") steel bonded to each surface; and thick aluminum surfaces. The panels were bonded using standard Amercom diffusion-bonding parameters resulting in well-bonded, high-quality material. The tooling used was the same as that used for the preliminary bend experiments.

Hat Forming: Initial attempts were made to fabricate the test-item hat sections from the 17.8 cm x 30 cm x 0.254 cm (7" x 12" x 0.10") composite panels which were clad with stainless-steel mesh and steel sheet. The total plate thickness was ~ 0.47 cm.

Figure 1. FINAL HAT CONFIGURATION

AMERCOM Hats

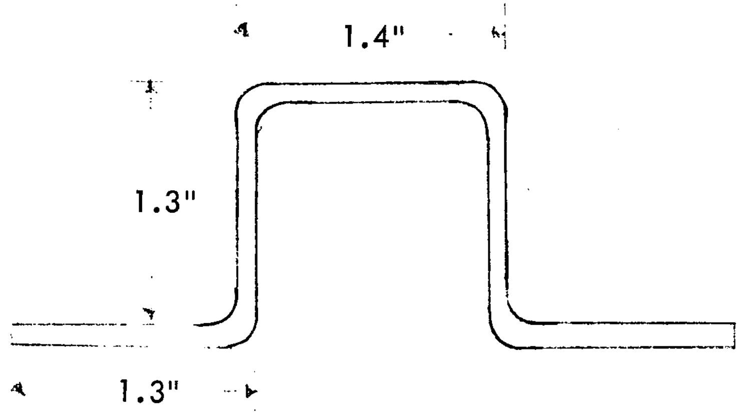


Test Length - 11.125"

Test Thickness - 0.11"

Note: Approximately 10 mils of extra surface Al or Al-SS on test hats.

McDonnell Douglas Astronautics Hats
Ref. NAS8-27735, Specimen #94-3-B



Test Length - 7.5"

Test Thickness - 0.105"

A series of bends were made on three panels at a temperature of $700^{\circ}K$ ($\sim 800^{\circ}F$) using a 1.6 cm (5/8") male tool. The first two plates were bent four separate times to form a hat section using a 2.54 cm (1") wide, V-shaped female die. In each case, the bends were successfully made but severe reverse bending adjacent to the bend area occurred. The third plate was bent using the same procedure but using a 3.17 cm (1.25") wide channel instead of the 2.54 cm (1.0") 'V'. Once again, the bends were satisfactory but severe reverse bending occurred. At this point, several experimental bends were made using 0.95 cm and 1.27 cm (3/8" and 1/2") male dies in the 3.17 cm (1.25") channel to vary the ratio of male die/channel width. This procedure resulted in several excellent bends, but was not conclusive. It did however point out that the wider channel was an improvement.

The resulting hat sections were badly deformed even though good, crackfree bends had been accomplished. It was necessary therefore, to modify the tooling and back-up technique to eliminate the reverse bending which ruined the initial hats. Additional bending experiments were conducted using a 1.27 cm (1/2") male die and the 3.17 cm (1-1/4") female channel. The back-up system used was the 0.038 cm (0.015") steel slip-sheet in contact with the female die, together with the 0.152 cm (0.060") aluminum between the steel and the composite. The results indicated that the 1.27 cm (1/2") die in the 3.17 cm (1-1/4") channel with the above back-up system could produce good bends repeatibly. However, to provide the required clearance necessary to make the final bends in the hats, it was necessary to use a "gooseneck" male die with a 1.27 cm diameter rod welded to it.

The final test hats were successfully produced using this system. It was found that at the $700^{\circ}K$ ($\sim 800^{\circ}F$) temperature the steel cladding was not necessary, and thus hats were made both with the mesh surfaces and with standard, bare aluminum surfaces. Five hats were produced, three for testing, one for delivery to NASA, and one for back-up. Table III summarizes the hat-forming trials.

Throughout the initial stages of this program, available tooling has been used with no attempt made to design and utilize tooling more suited for the characteristics of the B/Al composite. Subsequently, it has been determined that B-Al can be simply formed on standard tooling with a sufficient amount of heat input; i.e., as the temperature at which bends are being made increases, the critical nature of the tooling becomes less critical.

During the final stage of this study, it became evident that tooling relationships (such as male-to-female size ratios and the total composite-plus-backup thickness to female width) were critical to successful forming of thick B-Al. The proper selection of back-up material and female die width, as well as male/female ratio, controlled the composite reverse bending problem.

In the case of 'U' channels, the critical factor seems to be the relationship between the width of the female tool and the diameter of the male tool. A ratio of ~ 3 to 1 seems to be a workable range. The extra width of the female provides additional support far enough from the actual bend to minimize or eliminate the tendency to reverse bend, and allows the composite to form more uniformly.

Table III HAT FORMING

No.	Composite Thickness, in.	Surface Treatment	Backup	Top Cover	Temperature, °F	Appearance	Male Die/ Female Die	Comments
H-1a	0.10	mesh/steel	none	none	~800	reverse-bend	5/8/1.0"	Minor cracking, ~80° angle
H-2a	0.10	"	"	"	"	"	5/8/1.25"	No cracking at ~65° angle
H-3a	0.10	"	"	"	"	"	5/8/1.25"	No cracking at ~80° angle
H-4a	0.10	"	"	"	< 800	minor rev. bends	1/2/1.25"	Cracked
b	"	"	"	"	~800		"	No cracks
c	"	"	"	"	"	"	"	" "
d	"	"	"	"	"	"	"	" "
H-5a	0.10	mesh	0.06 stl.	none	~800	ok	3/8/1.25	No cracks
b	"	"	"	"	"	ok	"	" "
c	"	"	"	"	"	ok	"	" "
d	"	"	"	"	"	minor straightening	"	" "
H-6a	0.10	0.015 stl	none	none	~800	minor rev. bends	1/2/1.25	Cracked
b	"	"	"	"	"	"	"	No cracks at 65° angle
H-7a	0.10	6 mil Al	0.015 stl	none	~800	ok	1/2/1.25	No cracks
b	"	"	"	"	"	ok	"	No cracks
c	"	"	"	"	"	ok	"	No cracks
d	"	"	"	"	"	straightened	"	Cracked
H-8a	0.10	mesh	.08 Al/.015 stl	"	~800	cracked	1/2/1.25	---
H-9a	0.10	mesh	.08 Al/.015 stl	"	~800	good	1/2/1.25	Slight cracks
b	"	"	"	"	"	"	"	No cracks
c	"	"	"	"	"	"	"	Slight cracks
d	"	"	"	"	"	"	"	Cracks 1/2
H-10thru H-14	0.10	(one-mesh; 3 had 6-mil Al only)	"	"	"	minor surface cracks only	"	Hats being either tested or delivered to NASA

The actual forming of the final four test hats required several deviations from the original program. The effects of bend rate were seen to be negligible early in the tests. The effects of tool design (in particular when the proper male die to female die ratio was used) showed that neither mesh nor steel-bonded backup sheets are required if temperatures of approximately 700° to 800°F are applied. In addition, the type of composite backup and the use of a thin steel sheet between the male die and composite part are variables felt to be significant.

Although the bending experiments conducted resulted in a technique to permit forming of thick B-Al plate into structural hat sections, it became evident that additional study is desirable to develop techniques for lower-temperature forming which will result in even lower costs. Such additional effort would emphasize tool design and additional backup arrangements to produce consistent crack-free bends at lower temperatures.

C. Testing Procedure

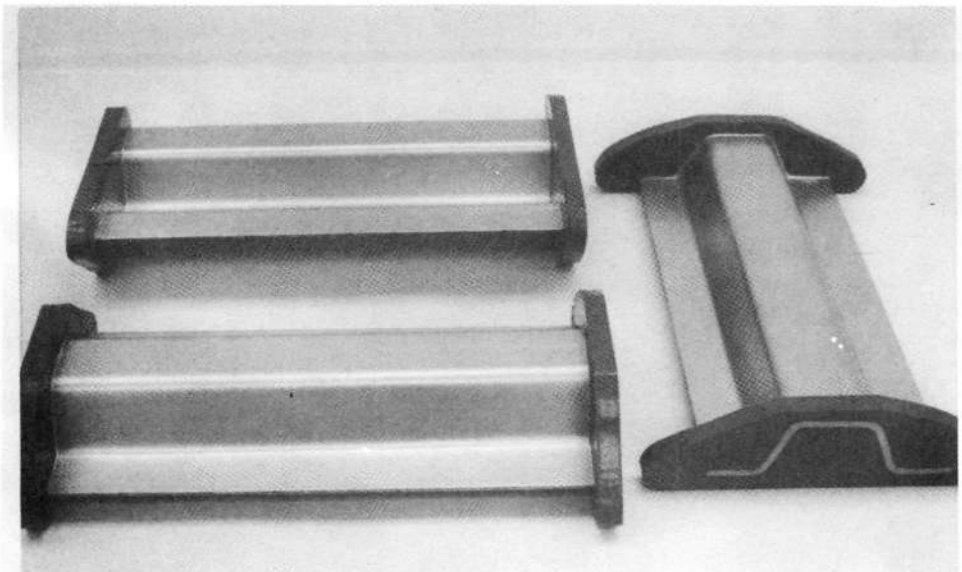
Specimen Preparation: The four hat stiffeners required for testing have been formed from sheets of 0.100" uniaxial B-Al with approximately 45 v/o, 5.6-mil B in 6061 matrix. The basic sheet (flat) is 12.25" long by 8" wide. The hat was shear-trimmed along the 12" sides; the ends were potted with approximately 3/4" of room-temperature curing epoxy, then machined flat and parallel.

The final hat configuration was chosen to closely represent a previous McDonnell Douglas Astronautics stringer-crippling test (MAC Spec. 94-3-B); this specimen was tested in a 7.51" length; the Amercom specimens are 11" test lengths which will decrease the anticipated crippling load somewhat. Figure 1 shows the McDonnell Douglas configuration and the final Amercom section. Because of a tooling limitation, the vertical legs were at approximately 80°. Minor twist from end to end of several specimens was noted; however generally good alignment and linearity were achieved. Figure 2 shows the hats before and after cleanup and potting.

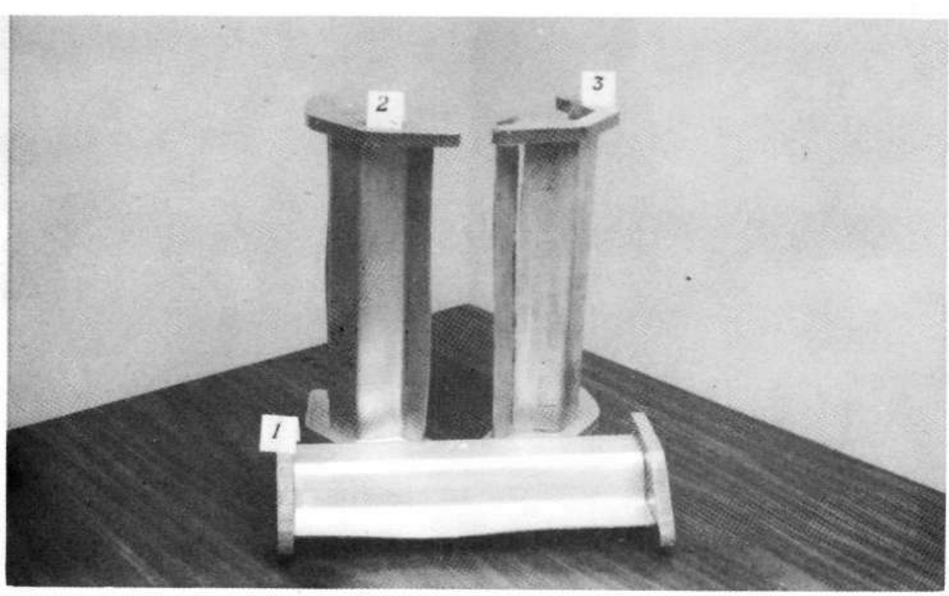
Testing Sequence: The testing sequence was as follows: The first test was carried to ultimate load (when buckling occurred it was defined as the maximum load achievable prior to notable decrease in load-carrying capability.) From these data the expected responses of the second and third specimens was determined. The second test specimen was then run to approximately 60% of compression/buckling yield strength, then cycled 25 times from 5% to 60%. The 26th cycle went to ultimate load. The final test item duplicated the second test, except that 50 cycles were run prior to determining the ultimate load capacity.

The tests were carried out by Magnaflux Corp. in Los Angeles under the cognizance of J. Dolowy from Amercom. A 200,000-lb testing machine was used for this test series; the machine bed and moving head were flat and parallel within 0.005"; and hard steel plates were placed between the testing machine and the composite part to prevent indenting of the test-machine surfaces. Dial gauges were placed at mid-height of the column to allow load vs. deflection data to be plotted. Ultimate load was defined when the column load-carrying capacity decreased more than 5%.

Figure 2. BEFORE AND AFTER: B-Al HATS



BEFORE TESTING



AFTER TESTING

D. Testing

The hat stiffener tests were carried out by Magnaflux Corporation, Los Angeles. The testing was done in a T. Olsen testing machine with a maximum load capacity of 200,000 lbs: the flatness and parallelism of the fixed bed to moving head were within 0.005" TIR (Table IV). This was checked by transversing the bed with the flat, magnetic-attach dial gauge (magnet disengaged) while noting the variations in the dial gauge which contacted the moving head. Two blocks of hardened steel were used to protect the machine beds from indenting by the composite shape. The machine, machine operator, hard plates, and three dial gauges were supplied by Magnaflux; J. F. Dolowy, Jr. of Amercom observed and set up all tests. A load in excess of 50,000 lbs, but below the mid-60,000 lb data point obtained by McDonnell Douglas Astronautics, was anticipated.

Hat No. 1:

The pertinent dimensional data for Hat No. 1 is given on Figure 3. The load was slowly and uniformly applied by the operator; dial-gauge readings were taken at approximately 10,000 lb. increments up to the range of impending crippling. During the application of the initial 10,000 lbs of load, a minor amount of creaking sound came from the points of load introduction, and the cap dial gauge showed $\sim$0.01", while the flange gauges showed $\sim$0.02". From 10,000 lbs on up to 40,000 lbs, the dial readings were essentially linear with the cap moving $\sim$0.003", and the flanges moving approximately 0.014". The initial large dial reading and sounds coming from the specimen ends can probably be attributed to minor irregularities in the hardened plates accommodating to the specimen ends, and either dial-gauge slop or minor waviness in the as-fabricated hat being removed during the initial load increment. After approximately ten minutes of loading, at 57,250 lbs, the No. 1 flange loudly popped out of plane and the load dropped slightly - no cracks or changes in specimen appearance were noted.

Hat No. 2:

This specimen was initially cycled 25 times to 60% of crippling as defined by the test of Hat No. 1 (57,250 lbs x 0.6 $\simeq$ 34,500 lbs). Approximately ten minutes were required to carryout the 25 cycles of load. In each cycle, following the first cycle, the slope of the load/deflection curve steepened with the flanges deflecting approximately 0.02" and the cap approximately 0.005". On the 26th cycle, the load was continuously applied up to 62,750 lbs, at which point the No. 1 flange loudly popped out of plane. Although a small decrease in load occurred, the hat was further loaded up to 66,600 lbs, where the No. 2 flange popped out of plane, and a crack occurred between the No. 1 flange and the upstanding leg. A surface crack along the mid-width of the cap (caused during the forming process) showed no signs of any change. (See Figure 4)

Hat No. 3:

The third test hat was similar to the first two, except for surface layers of Al-SS mesh bonded onto the composite during the initial fabrication cycle (see Figure 5). This part, when placed in the testing machine, didn't appear to "seat" or fit as well as

Table IV

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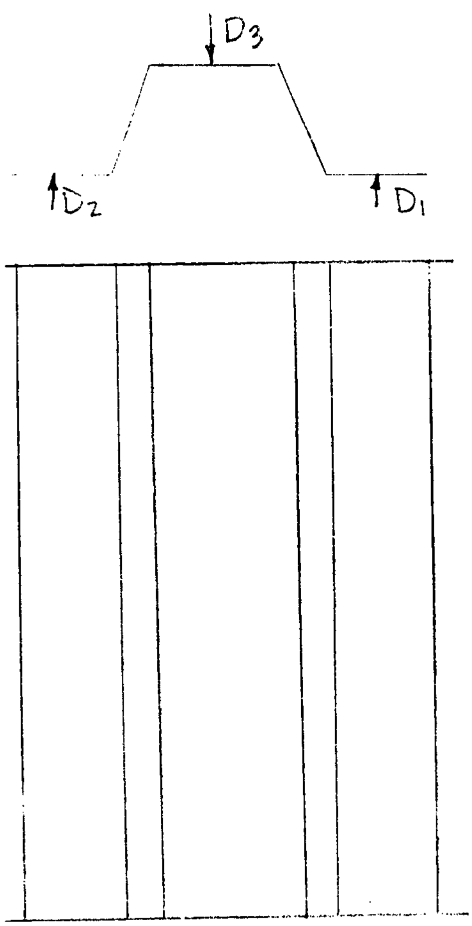
TEST SEQUENCE & EQUIPMENT - NASA HATS

10 March 1973

Test Machine:	T. Olsen, 4-post bed; 2-post moving head
Machine Capacity:	200,000 lbs.
Test Date:	12 March 1973
Machine Operator:	Jack Gerritsen
Engineer:	J. F. Dolowy, Jr.
Flat/Parallel Checks:	Via dial gauge check within 0.005". May have some minor irregularity due to bottom hard plate.

Test Set-up:



Toward dial is + for No. 1 and 2; but is minus for No. 3.

NASA HATS TEST

12 March 1973

Hat No. 1 - No mesh; 11-1/8" height; horizontal flange 1-1/4"; cap 1-3/8" and legs 1-1/4"

Minor surface cracks (short) on one horizontal flange; also minor back bend on cap, - no cracks.

Test: Record at 5K, 10K, 20K etc.......... UTS only

Time	Load	D1	D2	D3	D4	D5
9:47	5,000	0.020	0.020	0.12		
9:50	10,000	0.024	0.025	0.15		
9:52	20,000	0.030	0.030	0.17		
9:54	30,000	0.034	0.033	0.017		
9:55	40,000	0.039	0.036	0.018		
9:56	50,000	0.044	0.040	0.018		
9:57	57,250	#1 Flange popped out of plane.				

No cracks or other appearance changes occurred except for flange out of plane. Still good capability to carry load, ~ 1000 lb drop-off.

Figure 4

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NASA HATS TEST

12 March 1973

Hat No. 2 - No mesh; 11-1/2" height; horizontal flange 1-1/4", cap 1-3/8" and legs 1-1/4"

One flange had compression face cracks along ~3/4 length several layers deep.

Center cap showed back bend minor cracks. Legs to cap had minor compression side surface cracks.

Test: Cycle at 60% No. 1 UTS 25 times, then on 26th go to UTS.

Hat No. 1 UTS: 57,250 x .6 ≅ 34,500

Note dial gauges for any change during cycling.

	Time	Load (cycled)	D1	D2	D3
Cycle:	1st,	34,500	0.037	0.039	0.020
		2,000	0.014	0.022	0.012
	13th, 10:25	34,500	0.037	0.040	0.021
		2,000	0.017	0.025	0.015
	25th, 10:30	34,500	0.038	0.040	0.021

Comments on appearance after 25 cycles: Changed scale on machine; no visible changes in hat. Noted good fit with machine heads.

26th cycle data:

10:31	2,000			
	30,000	0.036	0.039	0.021
	40,000	0.040	0.041	0.022
	62,750	First flange popped out of plane .		

At 66,600, Second flange popped out of plane.

When second flange popped, the fracture along 1st flange occurred; that is when severe load decrease occurred. Surface cracks (from forming) did exist initially along the area of ultimate fracture.

Figure 5 **amercom, inc.**

NASA HATS TEST

12 March 1973

Hat No. 3 - Mesh.

Note: hat doesn't fit up as well with machine as did #1 & 2 !

11-1/4" height; horizontal flange 1-1/8", cap 1-3/8" and legs 1-3/8"

Minor surface cracks, both tensile cap to leg bends. Medium severe crack, one leg to flange tensile bend.

Minor over-heat area on one ℄ leg, ~2" from end potting.

Test: Cycle at 60% #1 UTS 50 times; then on 51st cycle go to UTS.

Hat #1 UTS: 57,250 x .6 ≅ 34,500

		Time	Load , lbs.	D1	D2	D3
Cycle:	1st	10:37	34,500	0.01	0.008	0.03
			2,000	0.008	0.008	0.005
	25th	10:48	34,500	0.008	0.008	0.006
			34,500	0.007	0.007	0.006
	50th		2,000	0.007	0.007	0.006

Comments on appearance after 50 cycles: No visible changes; fit-up was not as good as originally with machine, but adequate.

	Load , lbs.	D1	D2	D3
51st	2,000	0.007	0.007	0.006
	40,000	0.006	0.006	0.003
	45,000	0.005	0.005	0.0025
	55,000	Flange #1 out of plane		
	61,000	Flange #2 out of plane		
	69,100	Potting flew off.		

Hats No. 1 and 2; however, during the 50 cycles to 34,500 lbs, the load deflection curves were essentially straight with little or no shape change after the first cycle. A single data point (dial gauge #3) appears anomalous but was probably mis-recorded; i.e., should be 0.003". On the 51st cycle, the part was loaded to 55,000 lbs where the #1 flange flexed out of plane slightly without the loud sound of the previous tests. On continuous loading at 61,000 lbs, flange #2 moved out of plane and a slight crack developed on flange #1; however no load drop was noted. At 69,100 lbs a severe crack occurred in flange #1 and the end potting material fractured. The test was terminated at that point.

Generally, excellent correlation between the test parts was noted, i.e., initial crippling initiated at 58,000 lbs $\pm$3000 lbs; and the fact that all hats had the ability to carry increasing loads despite the initial out-of-plane flange is another example of the post buckled strength available in composites.

RECOMMENDATIONS

To fully utilize the capability shown by this initial evaluation, the following efforts are recommended:

1) Detailed evaluation of the tool and back-up design for lower temperature forming.

2) Thoroughly evaluate the forming capability of materials between 0.05" and 0.10" the major area of interest presently in real structures.

3) Fabricate and test longer hats and channels (3 ft or 5 ft would be more representative of real structure).

4) Fabricate and test hats with attached face plates (panel simulators).