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SELECTIVE REINFORCEMENT OF ALUMINUM I-BEAMS WITH GRAPHITE-ALUMINUM COMPOSITE WIRE

JUNE 1976

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ABSTRACT

Standard 6061 aluminum I-beams were selectively reinforced on the flanges with single strand T50 graphite/6061 aluminum composite wire reinforcements by utilizing a hot isostatic pressing (HIP) process. Preliminary mechanical hot pressing trials on graphite-aluminum sandwich construction panels were conducted to investigate the effects of both solid and liquid state processing parameters on composite flexural properties. Mechanical test data on these panels indicated that solid state bonding conditions resulted in higher flexural strength and modulus than liquid state conditions. Based on these results, lay-up and containment was designed to hot isostatically press in the solid state 0.040" (0.102 cm.) thick graphite-aluminum layers to the flanges of four standard 6061 aluminum I-beams. Metallographic examination of sections from the HIP processed I-beams showed consolidation had been achieved between the graphite-aluminum composite wires and to the I-beam flange interfaces. However, some sections showed micro-cracks within the composite layers and at the composite layer/I-beam flange interface due to high residual stresses induced during thermal contraction of the I-beam upon cooling from the HIP processing temperature. Consideration of thermal expansion data and relative masses for the T50 graphite/6061 aluminum composite reinforced I-beams support these observations. It was concluded that the process feasibility of selectively reinforcing a standard aluminum I-beam with graphite-aluminum composite layers via hot isostatic pressing was successfully demonstrated. It is recommended that a more moderate modulus fiber such as T300 be considered for the fabrication of selectively reinforced hardware. In addition, design studies directed towards minimizing thermal and mass effects should be conducted on any future work to selectively reinforce structural sections.

FOREWORD

This is the final technical report on Contract No. DAAG46-76-C-0060. The work was performed in the laboratories of Fiber Materials, Inc. and covers the period 13 March 1975 to 12 April 1976. The program was administered by the Army Materials and Mechanics Research Center, Watertown, Massachusetts with Mr. A. Levitt as Contracting Officer's Representative (Technical Supervisor).

Mr. Horst Gigerenzer of Fiber Materials, Inc. was the program manager. Mr. Gary C. Strempek acted as the project engineer.

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FINAL REPORT

Technical Program: DAAG46-75-C-0060

Program Manager: H. Gigerenzer

Project Engineer: G. C. Strempek

1.0 OBJECTIVE:

The objective of this work was to demonstrate the feasibility of the selective reinforcement of aluminum 'I'-beams with a graphite-aluminum composite by developing fabrication process parameters to bond T50 graphite/6061 Al reinforcements to standard 6061 Al I-beam flanges.

2.0 SUMMARY:

New technology was developed at the FMI chemical processing laboratories which allowed the production of 10,000 feet (3050 meters) of single strand T50* graphite/6061 aluminum composite wire. The composite wire was produced by optimizing parameters in the Lachman coating process in conjunction with a 6061 Al melt infiltration process. Composite wire properties of 150,000 psi (1034 MPa) at 40 volume percent fibers were obtained.

Solid and liquid state fabrication parameters were investigated for bonding high strength graphite-aluminum wire reinforcements to standard 6061 aluminum I-beam flanges by initially vacuum hot pressing test panels {0.5" x 4" x 0.125" (1.27 cm. x 10.2 cm. x 0.318 cm.)} of sandwich construction (i.e., a composite wire layer bonded to both sides of a pure 6061 aluminum core). Microstructural examinations of these panels fabricated by both solid and liquid state processes revealed well-bonded structures. Flexure specimens machined from the panels

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*Trademark of the Union Carbide Corporation were subjected to four point bending to determine the flexural modulus and strength of the composite sandwich panels for both processes. The results obtained indicated that higher values of modulus and strength were achieved for T50 graphite/6061 aluminum panels when processed under near solid state conditions than when processed under liquid state bonding conditions.

Based on these results, lay-up and containment were designed for 0.040" (0.102 cm.) thick T50 graphite/6061 aluminum wire reinforcement layers to be hot isostatically pressed (HIP) in the solid state to each flange of four standard 6061 aluminum I-beams, 20" (50.8 cm.) in length. The graphite-aluminum layer for each I-beam flange was layed-up and HIP bonded to the flanges in situ rather than HIP bonding prefabricated hot pressed graphite-aluminum panels to the I-beam flanges. Initial metallographic examinations of I-beam end sections from HIP processed graphite-aluminum reinforced I-beams showed excellent consolidation of the composite wires within the layer and good bonding of the T50 graphite/6061 Al layer to the 6061 Al I-beam flange surfaces. These results were as expected from previous observations of hot pressed sandwich panels. Further metallographic examinations of random I-beam sections, however, revealed areas showing micro-cracks running through the composite layer in the longitudinal plane and occasionally along the graphite-aluminum layer/ I-beam flange interface. These defects are attributed to stresses induced during thermal contraction of the I-beam on cooling from the HIP processing temperature, thus causing cracking within the graphite-aluminum layer along weak transverse directions of the composite.

It was concluded that the process feasibility of selectively reinforcing standard 6061 aluminum I-beams with graphite-aluminum was successfully demonstrated. The occurrence of the micro-cracks in the graphite-aluminum layers is unique and inherent to the materials system being processed. When a high modulus fiber such as T50 (50 Msi modulus) is utilized for the selective reinforcement, high residual thermal stresses are induced. It is recommended that lower modulus fibers (such as T300) be considered, {34 Msi (234 GPa) modulus}, for the fabrication of any future selectively reinforced hardware. In addition, design studies directed towards minimizing thermal stresses and relative mass effects should be conducted for selectively reinforced composite structures.

3.0 RESULTS AND DISCUSSION:

3.1 Graphite-Aluminum Composite Wire Development

The development of strong single strand T50 graphite/6061 Al composite reinforcing wire was achieved by optimizing the operating parameters in the liquid metal infiltration process.

The primary factors which controlled the fiber content and consequently, the mechanical strength of the single strand composite wire, were the infiltration speed, back tension on the yarn, and the temperature of the 6061 aluminum melt. The set of optimized parameters arrived at were 36 inches (91.4 cm.) per minute, three pounds (1.36 kg.) and 1220°F (660°C), respectively. The following wire properties were obtained:

Linear Density	0.119 lb./in. (0.213 g/meter)
Cross-Sectional Area	1.5×10^{-4} in.^{2} (9.9×10^{-4} cm.^{2})
Volume Percent Fibers	40
Breaking Load	22.5 lbs. (10.2 kg.)
Tensile Strength	150,000 psi (1034 MPa)

Figure 1 illustrates a typical transverse section of the single strand T50 graphite/6061 Al wire reinforcement produced by the above process. Of particular interest is the even fiber distribution and the lack of areas of excess aluminum. These characteristics contributed towards achieving the high volume percent fibers with resultant high tensile strengths.

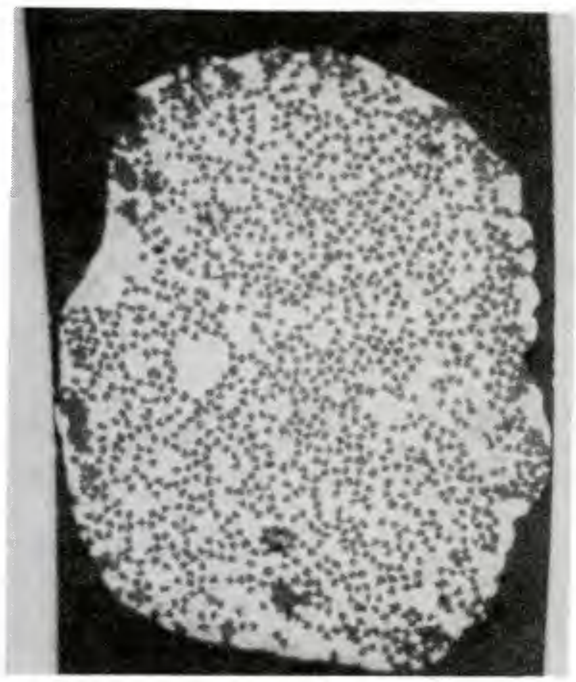

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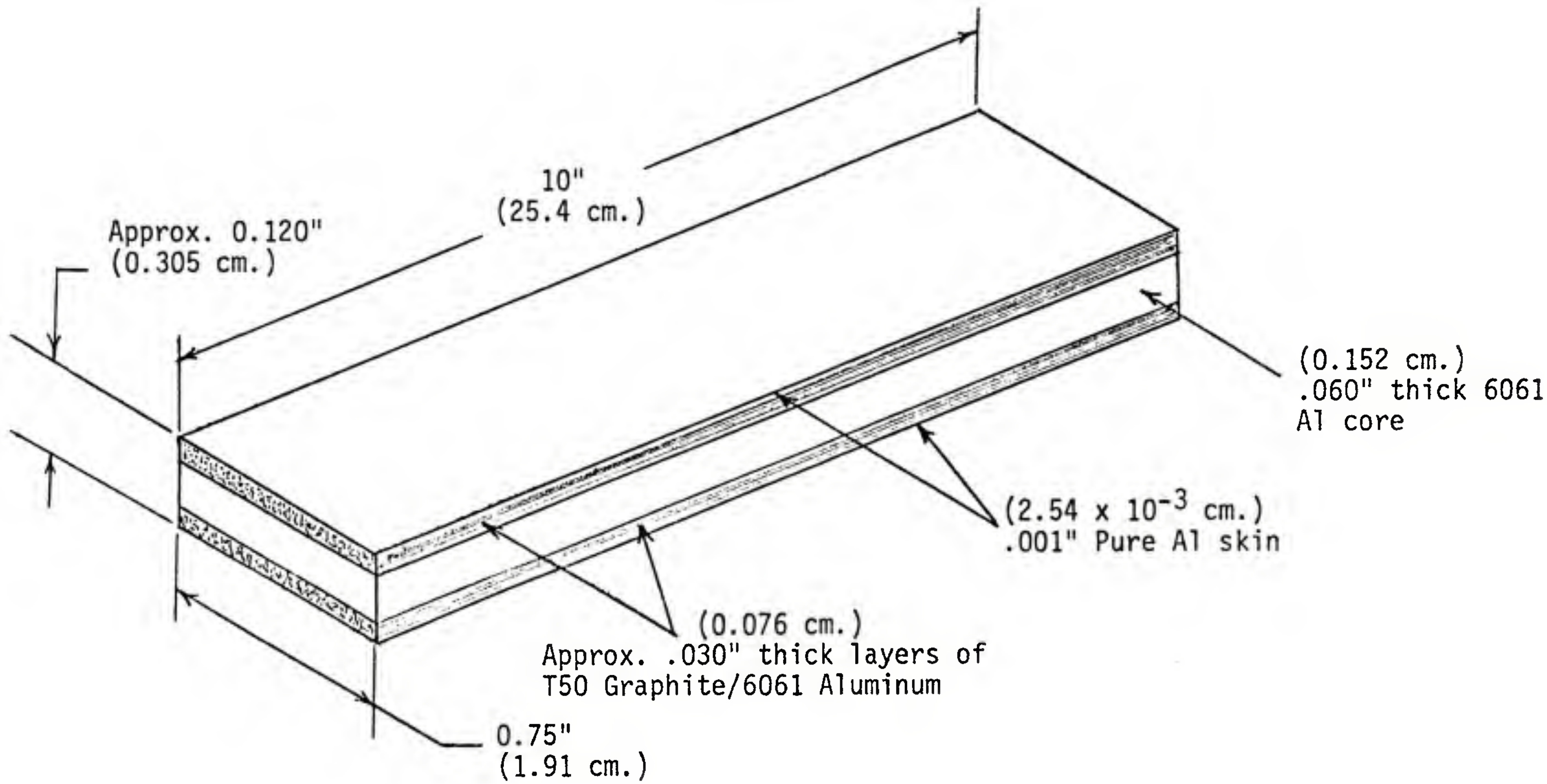
Figure 1: Typical transverse section of FMI single strand T-50 Graphite/ 6061 Aluminum composite wire.

3.2 Lay-Up of T50 Graphite/6061 Aluminum Test Panels

Graphite-aluminum test panels {pressed oversize to 0.75" x 10" x 0.125" (1.91 cm. x 25.4 cm. x 0.318 cm.)} utilizing single strand T50 graphite/6061 aluminum composite wire were fabricated by both solid and liquid state vacuum mechanical hot pressing to establish optimum processing conditions for I-beam reinforcement. The panels were of a sandwich construction (see Figure 2), consisting of a 6061 aluminum core, the two opposite faces of which were clad with a layer of T50 graphite/6061 aluminum, thus simulating an I-beam configuration. The reinforcement layers on each 6061 aluminum core face were produced by stacking three layers of T50 graphite/6061 aluminum composite wire {approximately 0.014" (0.036 cm.) per layer} by aligning each wire individually in place, pre-bonding the composite wires to the 6061 aluminum core surfaces and to each other with a volatile binder of polymethylmethacralate (PMA). These layers consolidated to approximately 0.030" (0.076 cm.) thick after pressing. Upon completion of construction, the panels were wrapped with 0.001" (2.54×10^{-3} cm.) thick pure aluminum foil, inserted into a titanium pressing can and evacuated to a pressure of 0.1 to 0.2 torr. The pressing can was heated to 752^{o}F (400^{o}C) for 1/2 to 1 hour to volatilize the PMA binder. The complete removal of the binder could be monitored by observing the initial large increase in vacuum pressure (up to ~ 1 torr), followed by rapid recovery, leveling off to below 0.1 torr vacuum pressure. This pressure change cycle took approximately 45 minutes to complete. After consolidation, the panels were removed and had the dimensions 0.75" x 10" x 0.125" (1.91 cm. x 25.4 cm. x 0.318 cm.).

3.3 Solid State and Liquid State Bonding Trials of T50 Graphite/6061 Aluminum Wire Reinforcements to 6061 Aluminum Test Panels

Near solid state diffusion bonding of T50 graphite/6061 aluminum wire reinforcements to the 6061 aluminum core was achieved with the following



NOTE: Dimensions given are approximate values of the actual pressed panels.

FIGURE 2: Lay-Up of T50 Graphite/6061 Aluminum Sandwich Test Panel

temperature, $T = 1094^{o}F$ ($590^{o}C$)

pressure, $P = 4000$ psi (27.6 MPa)

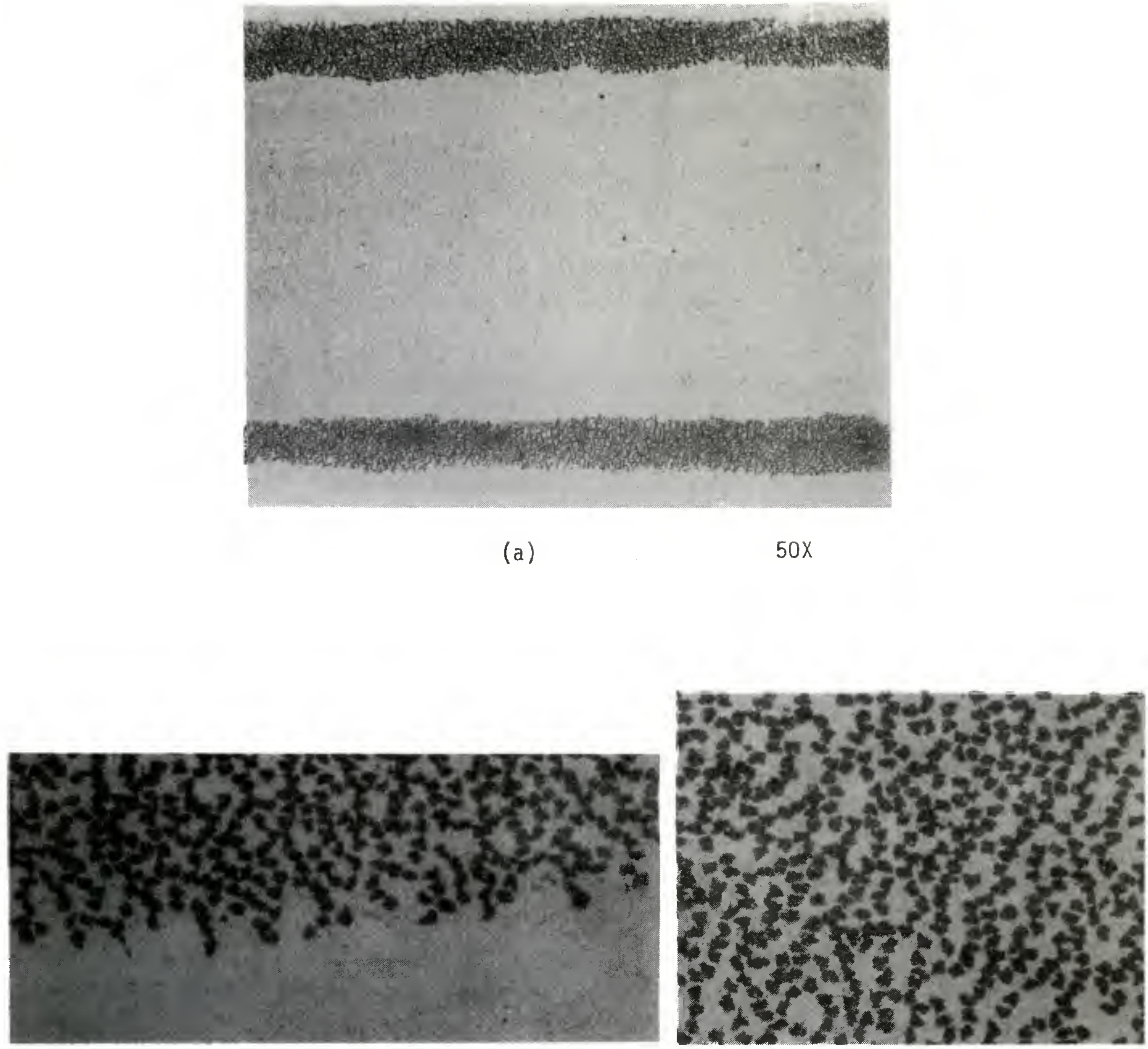
time, $t = 40$ min.

The 6061 aluminum solidus temperature, $T_S = 1080^{o}F$ ($582^{o}C$). Preliminary pressing trials indicated that diffusion bonding of 6061 aluminum does not occur below approximately $1085^{o}F$ ($585^{o}C$) for the pressure and time conditions investigated. Detailed metallographic examinations of the composite layer/core interfaces, (Figure 3a and 3b), and the microstructures of the consolidated T50 graphite/6061 aluminum composite layers, (Figure 3c), showed no areas of debonding, indicating that well-bonded composite panels had been achieved under near solid state bonding parameters.

Liquid state processing of T50 graphite/6061 aluminum by hot pressing requires temperatures in excess of $1112^{o}F$ ($600^{o}C$) (Al 6061 liquidus temperature $T_L = 1200^{o}F$ ($649^{o}C$). Processing graphite-aluminum with titanium boride interface barriers above $1112^{o}F$ ($600^{o}C$), can result in rapid degradation of fiber strength due to excess formation of aluminum carbide at the fiber/matrix interface. Therefore, it is most desirable to keep processing temperatures below $1112^{o}F$ ($600^{o}C$).

In order to investigate liquid state processing below $1112^{o}F$ ($600^{o}C$), a small amount of Al 10.9% Si eutectic liquid (eutectic temperature $T_E = 1071^{o}F$ ($577^{o}C$) was introduced during the hot press processing of the second set of panels. The aluminum-silicon was introduced in the form of a thin coating {0.001" (2.54×10^{-3} cm.) thick} applied in slurry form to each graphite-aluminum wire element. The slurry consisted of a homogeneous mixture of AlSi powder and PMA binder.

Liquid state hot press processing of T50 graphite/6061 aluminum to 6061 aluminum cores was achieved utilizing the following process parameters:



(a) 50X

(b) 400X

(c) 400X

FIGURE 3: Transverse Microstructures* of 6061 Aluminum Panel Reinforced With Two Composite Layers of T50 Graphite/6061 Aluminum Bonded By Solid State Hot Pressing: (a) Macrosection, (b) Composite/Core Interface, (c) 6061 Al/T50 Graphite Composite Layer.

*Note: These microstructures are from preliminary panels where the composite layer was less than 0.030" (0.076 cm.) thick.

temperature, $T = 1094^{o}F$ ($590^{o}C$)

pressure, $P = 3500$ psi (24.1 MPa)

time, $t = 5$ min.

These parameters show that liquid state hot pressing allows lower pressures and shorter pressing times to achieve full consolidation as is evident from the microstructural examinations, (Figure 4), of these panels. By minimizing both pressure and time at temperature during processing, less overall degradation of the composite can be expected as a result of processing.

Flexure specimens {0.5" x 4" x 0.120" (1.27 cm. x 10.2 cm. x 0.305 cm.)} machined from panels representing both solid and liquid state processing were tested in four point bending to determine flexural modulus and strength. The values obtained are tabulated below as follows:

Hot Press Processing	Flexural Modulus[1] x 10^6 psi	Flexural Strength[2] (psi)
Solid State	28.9 (199 GPa)	68,400 (472 MPa)
Liquid State	23.6 (163 GPa)	63,900 (441 MPa)

NOTES:

1. Average value of four measurements
2. Average value of two measurements

It is apparent from these results that higher flexural properties are obtained for the solid state processed T50/6061 aluminum sandwich panels than for similarly constructed panels processed by liquid state bonding. The reason for this difference in properties between the two processes is not clear, since liquid state processing times are much shorter than those used under solid state conditions. The kinetics of chemical reactions, however, are higher at liquid metal temperatures. Nevertheless, for both

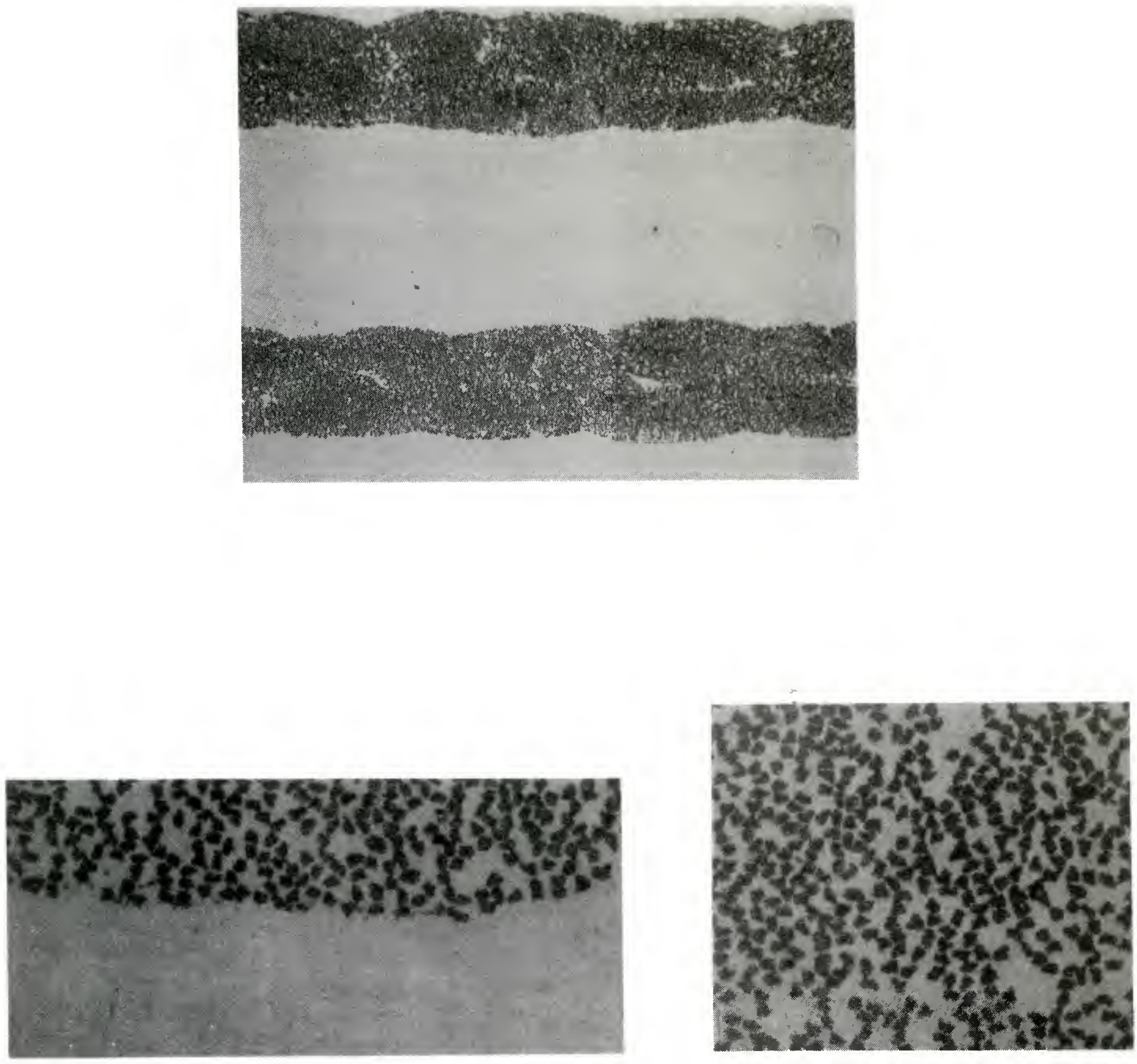


FIGURE 4: Transverse Microstructures* of 6061 Aluminum Panel Reinforced With Two Composite Layers of T50 Graphite/ 6061 Aluminum Bonded By Liquid State Hot Pressing: (a) Macrosection, (b) Composite/Core Interface, (c) 6061 Al/T50 Graphite Composite Layer.

*Note: These microstructures are from preliminary panels where the composite layer was less than 0.030" (0.076 cm.) thick.

cases, the flexural modulus is considerably higher than that of unreinforced 6061 aluminum {E = 10 x 10^6 psi (69.0 GPa)}.

These results demonstrated that substantial improvements in flexural properties were achieved for small 6061 aluminum panels when reinforced with thin face layers of T50 graphite/6061 aluminum composite. Specifically, these results show that to optimize flexural properties in composite panels, solid state diffusion bonding is the preferred processing technique for the reinforcement of standard 6061 aluminum I-beam flanges with T50 graphite/6061 aluminum composite layers.

3.4 Hot Isostatic Pressing of T50 Graphite/6061 Aluminum Wire Reinforcements to Standard 6061 Aluminum I-Beam Flanges

The structural reinforcement as required by contract (see Figure 5), of standard 6061 aluminum I-beams was accomplished by hot isostatically pressing in the solid state, graphite-aluminum reinforcement wires, in situ, to each I-beam flange. This route was chosen after careful consideration of previous results obtained on sandwich test panels and on the effect of extended processing conditions in achieving optimized flexural properties for final I-beam reinforcement. The merit of this approach lies in the fact that the T50 graphite/6061 aluminum reinforcements are subjected to only one processing cycle at pressure and temperature rather than to a double cycle (i.e., by first mechanically hot pressing panels followed by hot isostatic pressing to the flanges). The success probability of transferring maximum wire reinforcement properties to I-beam flanges via a one-step process is considerably higher than when utilizing two-step processing.

Suitable containment was designed and constructed in which the graphite-aluminum reinforcement layer {final pressed thickness 0.040" (0.102 cm.)}

NOTE: Al Top Layer on Flange as Required

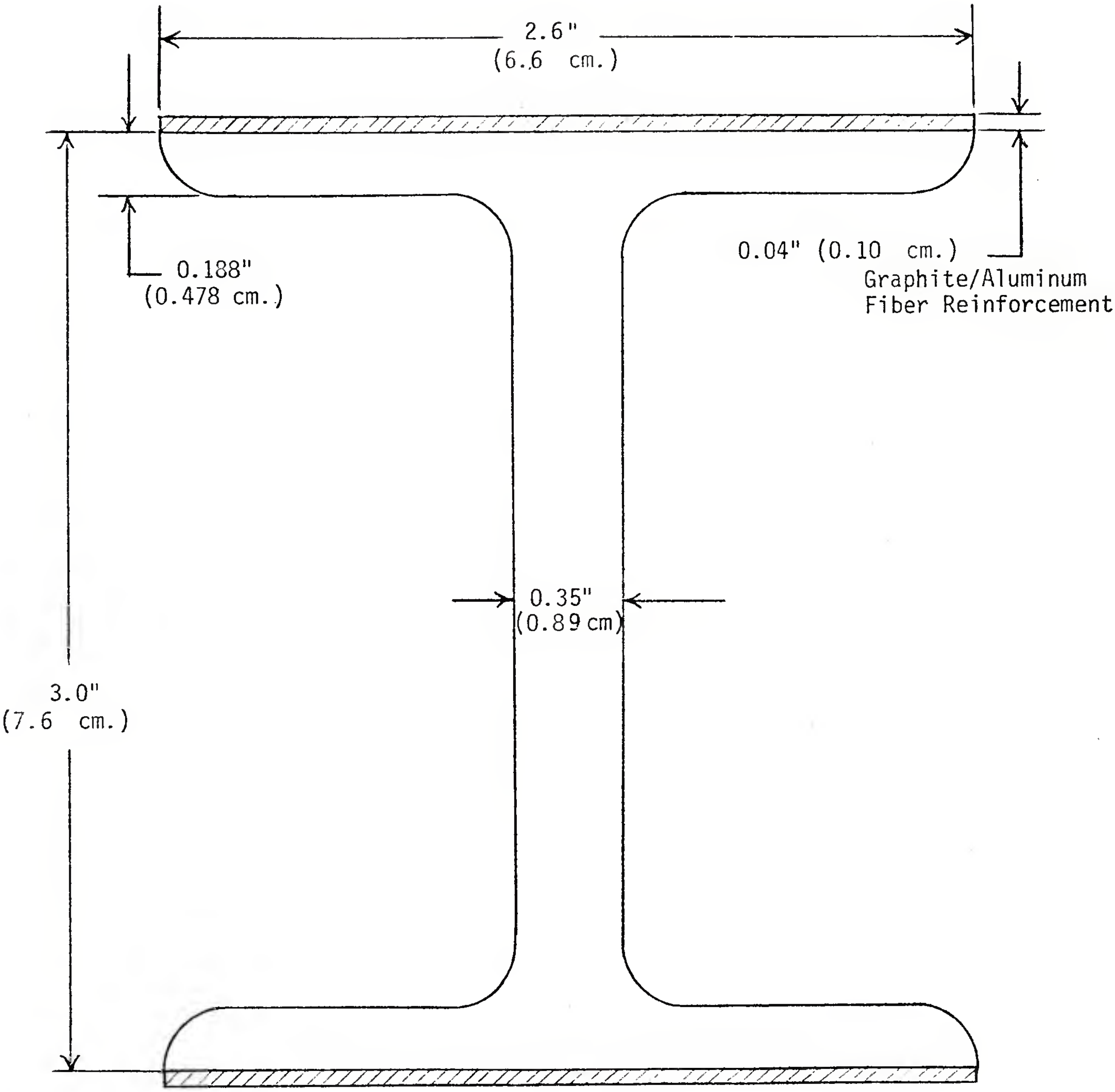


FIGURE 5: Schematic Drawing of Cross Section of 3" x 2.6"(7.6 cm. x 6.6 cm.) Flange 6061 Aluminum I-Beam With Unidirectional Graphite-Aluminum Laminates Bonded to its Flanges. Length of Reinforced Beam is 20" (50.8 cm.).

could be layed-up and held in place during HIP processing to the flanges of the I-beams (see Figure 6). The seams of the enclosure were electron beam welded to yield a vacuum-tight encapsulation for the graphite-aluminum reinforcements. Helium mass spectrometry leak check analysis was employed to assure that the welded seams were vacuum-tight prior to HIP processing of the I-beams.

Solid state HIP processing parameters which resulted in well consolidated graphite-aluminum layers bonded to the I-beam flanges were as follows:

temperature,	$T = 1030^{o}F$ ($544^{o}C$)
pressure,	P = 10,000 psi (69.0 MPa)
time,	t = 60 min.

Four I-beams were HIP processed under these conditions. Figure 7 shows two of the four I-beams after final machining while Figure 8 shows a close-up typical of one of the I-beam cross-sections with the 0.040" (0.102 cm.) thick graphite-aluminum layer exposed.

Detailed metallographic examinations of end sections of the HIP processed I-beams revealed well-bonded graphite-aluminum structures with respect to the consolidation of graphite-aluminum wires and bonding of the graphite-aluminum layers to the I-beam flanges (Figure 9). A homogeneous fiber distribution within the consolidated layer was typical, and the absence of voids was noted. Further metallographic examinations, however, of random sections of a trial I-beam, revealed areas within the graphite-aluminum layers which contained micro-cracks. These cracks generally propagated through the graphite-aluminum layer parallel to the reinforcement layer/I-beam flange interface (Figure 10a) and occasionally along the interface (Figure 10b). These cracks are not attributed to any short-

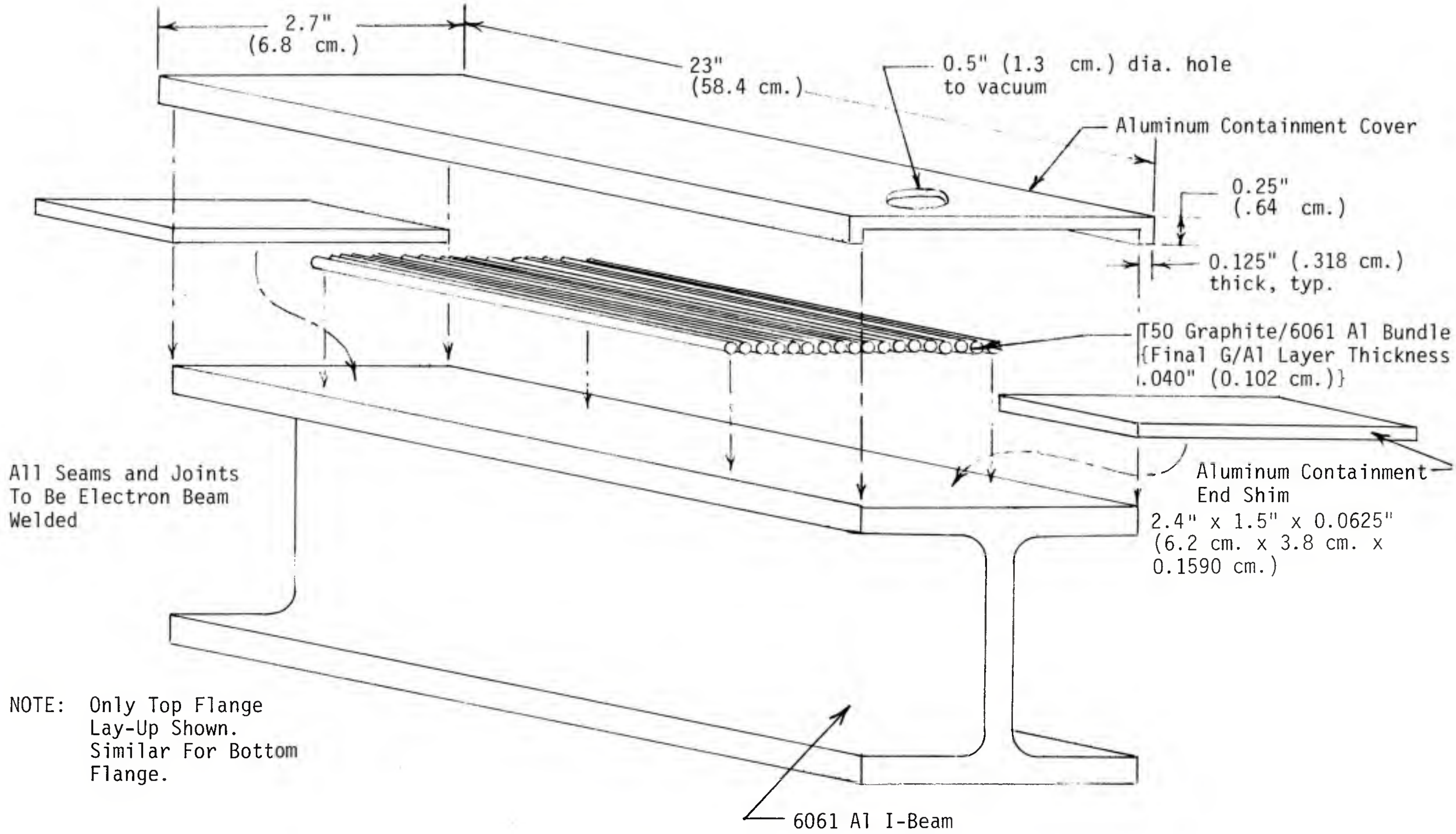


FIGURE 6: LAY-UP AND CONTAINMENT DESIGN FOR GRAPHITE-ALUMINUM REINFORCEMENT LAYER IN PREPARATION FOR HOT ISOSTATIC PRESSING TO I-BEAM FLANGES.

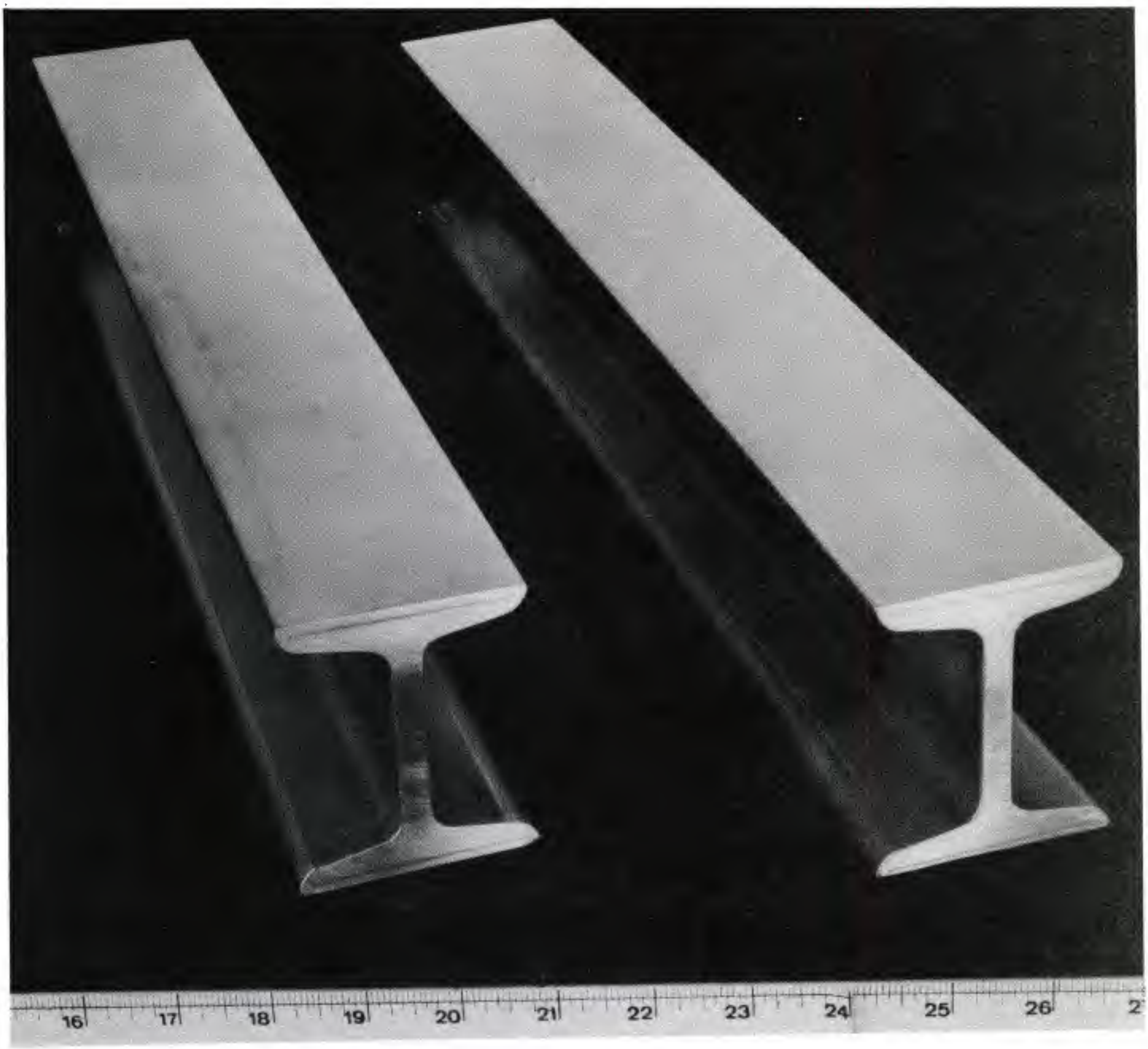


FIGURE 7: Two of the Four 6061 Aluminum I-Beams Reinforced With Flange Layers of T50 Graphite/6061 Aluminum Layers Processed by Hot Isostatic Pressing (HIP).

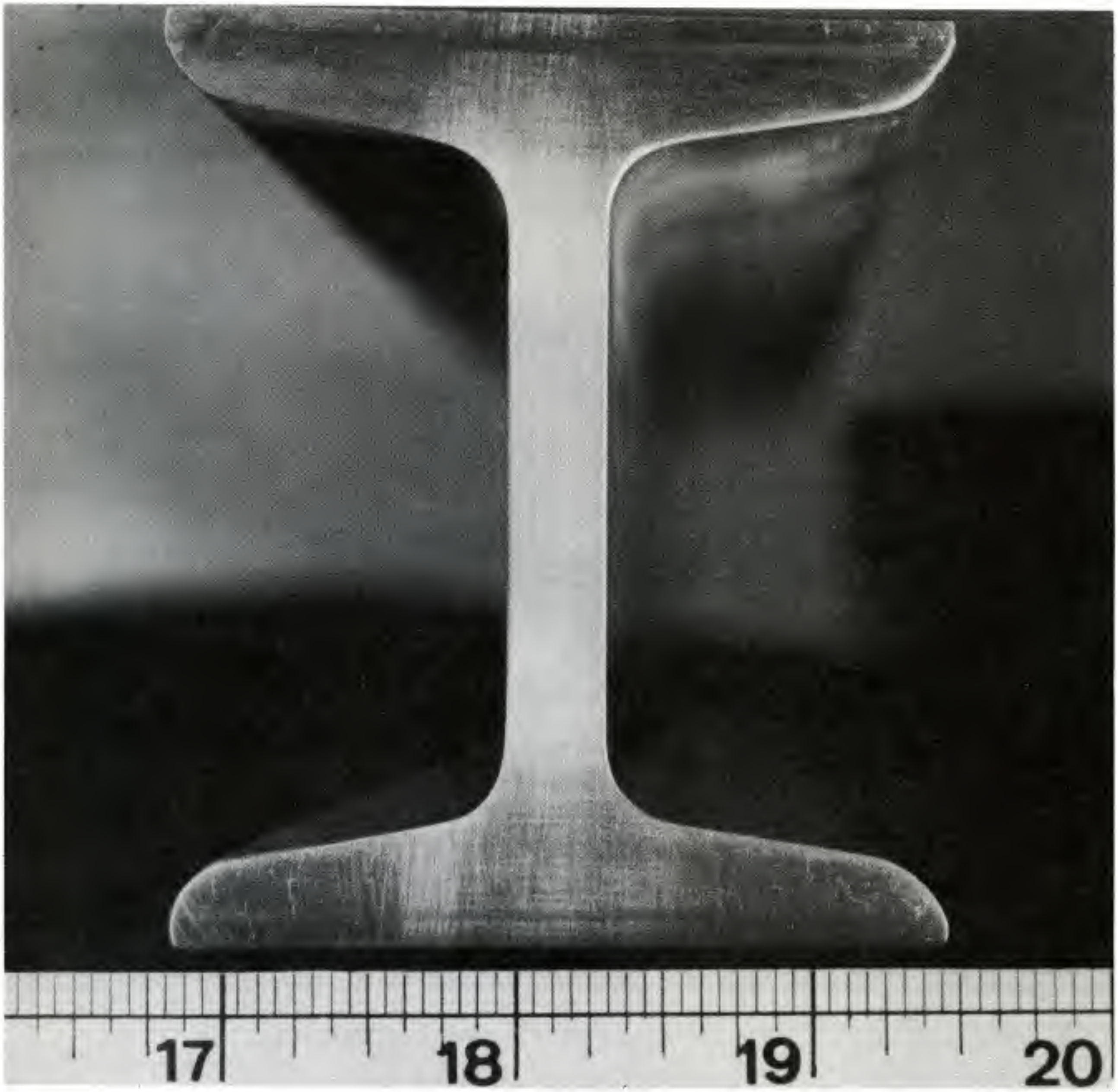


FIGURE 8: TYPICAL CROSS-SECTION OF 6061 ALUMINUM I-BEAM REINFORCED WITH 0.040" (0.1016 cm.) THICK LAYER OF T50 GRAPHITE/6061 ALUMINUM.

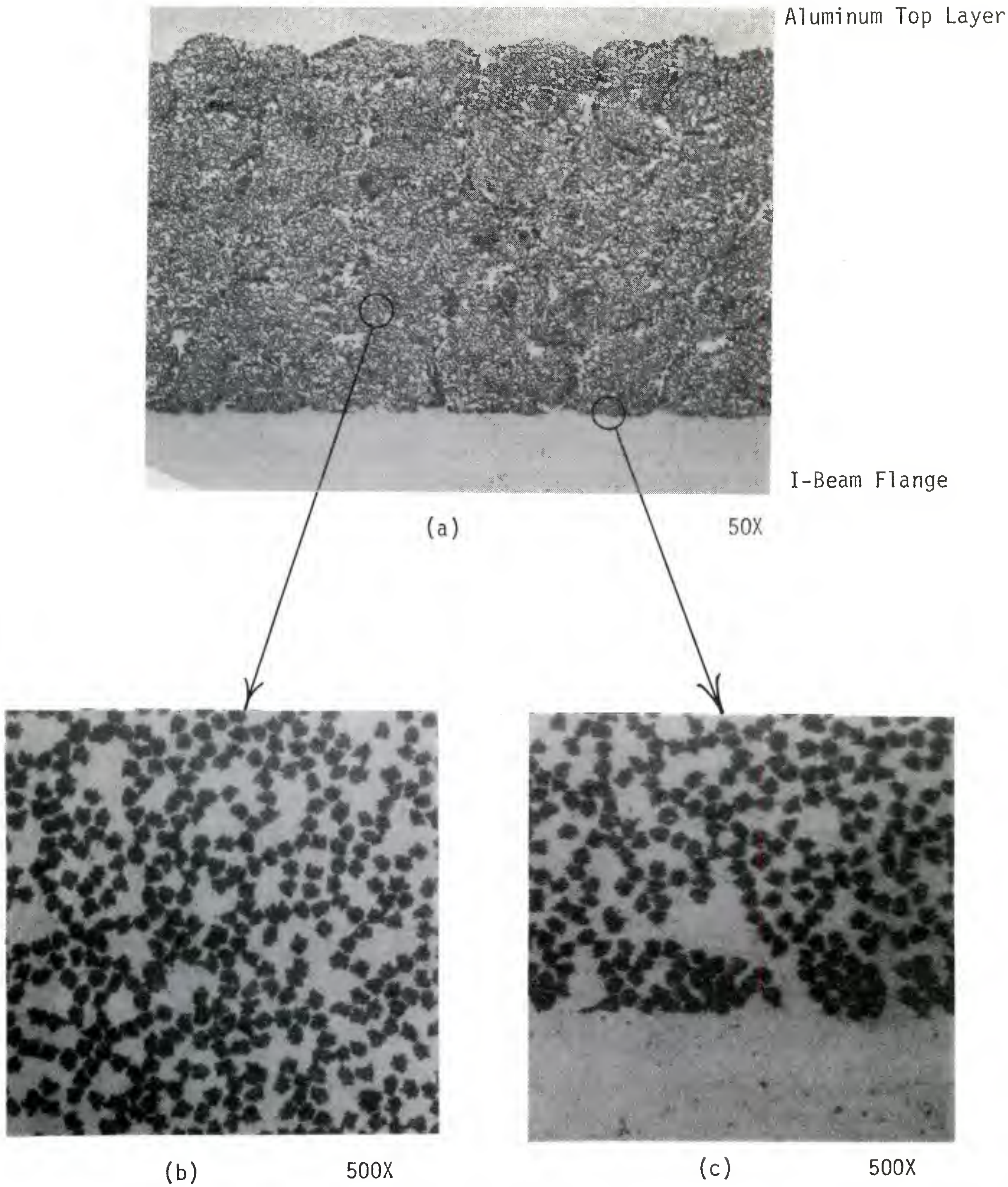


FIGURE 9: T50 Graphite/6061 Aluminum I-Beam Layer (a), Showing Good Bond Within Layer, (b), and Bond to 6061 Aluminum I-Beam Flange, (c).

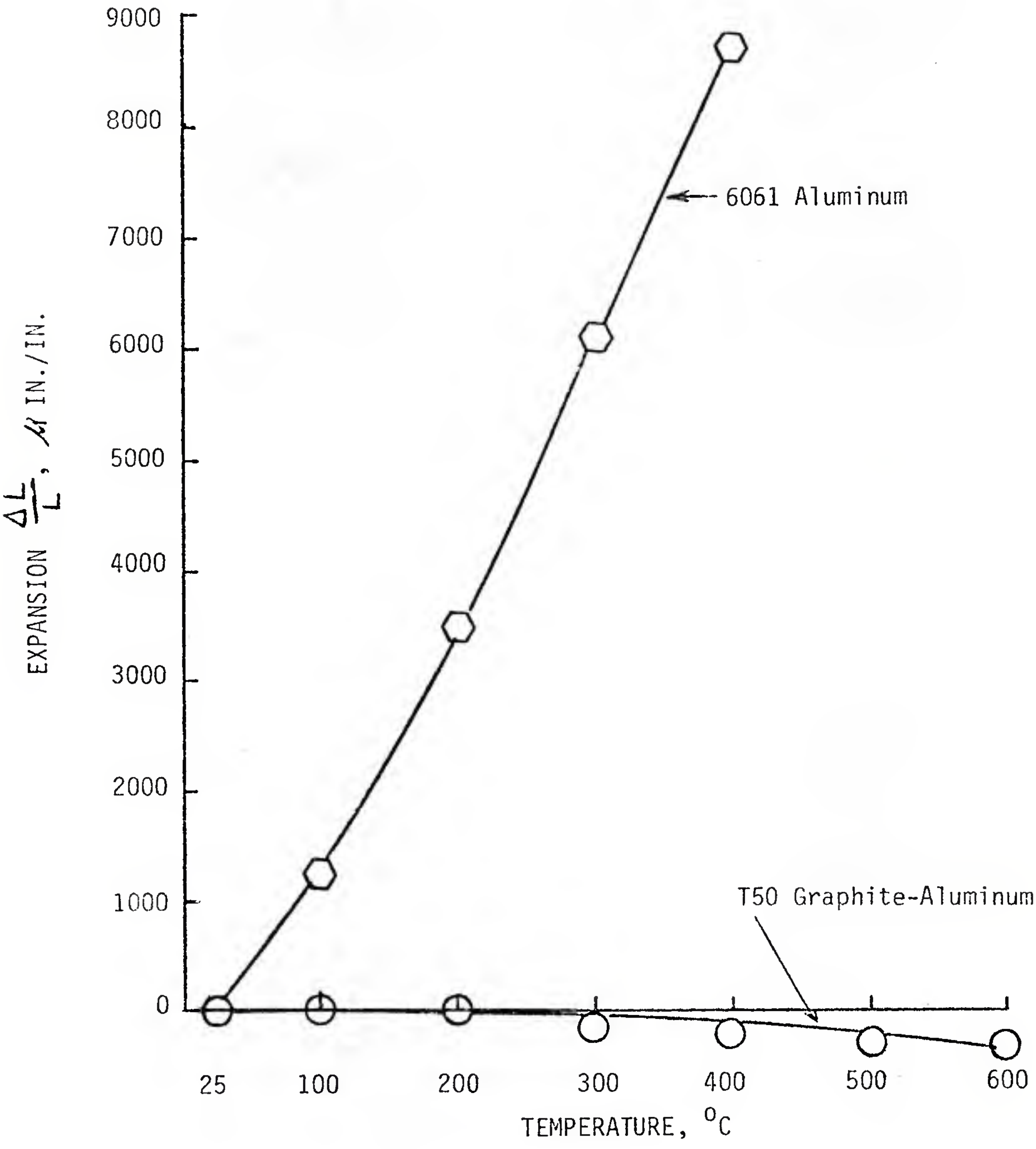


FIGURE 11: Thermal Expansion[1], $\frac{\Delta L}{L}$, as a Function of Temperature.

[1]Aerospace Corporation Data

relatively more positive coefficient of thermal expansion than T50 and promises improved transverse strength levels for graphite-aluminum composites. The thermal mis-match effect causing cracking in the composite layers seems to be peculiar to the selective reinforcement approach of structural hardware. At FMI, the successful fabrication of plates, bars, and most recently, tubes from T50 graphite-aluminum has shown no such behavior as observed in this investigation.

To minimize the risk of further propagation of cracks in the aluminum-graphite layers of the reinforced beams, additional aluminum was left on the faces and sides of the flanges, Figure 8. Allowance for the effects of this additional aluminum will be necessary in the comparison with unreinforced standard I-beams during structural testing at AMMRC. Difficulties were encountered in machining one of the faces of one of the beams due to the residual stresses present. Relief of stress during machining of the face caused distortion of the face and unavoidable tool marks and breaking through to the composite layer at the very end of the beam.

4.0 CONCLUSIONS:

1. Process feasibility has been demonstrated by consolidating single strand T50 graphite/6061 aluminum composite wire reinforcements into thin reinforcement layers. These layers can be bonded to the flanges of standard 6061 aluminum I-beams via a one-step hot isostatic pressing process utilizing the following solid state process parameters; pressure = 10,000 psi (69.0 MPa), temperature = 1030^{o}F (554^{o}C), and time = 60 minutes.

2. A high level of residual stress exists within the T50 graphite/6061

aluminum I-beam flange reinforcement layers causing cracking within the composite layers. The cause for this condition is partly due to the existence of an inherent large mis-match of thermal expansion/contraction behavior and partly to a relative mass effect between the composite reinforcement layer and the bulk of the aluminum I-beam.

3. The T50 graphite/6061 aluminum I-beam flange reinforcing layers should have additional aluminum on their sides to minimize the risk of micro-crack propagation.

4. The flexural strength and modulus are higher for 6061 aluminum test panels reinforced with face layers of T50 graphite/6061 aluminum when hot pressed under near solid state conditions than when processed under liquid state bonding conditions.

5.0 RECOMMENDATIONS:

1. For the selective reinforcement of aluminum structural hardware, high strength, moderate modulus graphite fibers should be considered such as T300 {E = 34 Msi (234 GPa)} rather than high strength, high modulus fibers such as T50 {E = 50 Msi (345 GPa)}.

2. Design studies involving thermal expansion and mass effect considerations should be an integral part of future work to selectively reinforce structural sections.

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SELECTIVE REINFORCEMENT OF ALUMINUM I-BEAMS WITH GRAPHITE-ALUMINUM COMPOSITE WIRE
H. Gigerenzer and G. C. Strempek
Fiber Materials, Incorporated
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Technical Report AMMRC CTR76-19, June 1976, 22 pp - illus - tables, Contract DAAG46-75-C-0060
D/A Project 1T162105AH84, AMCMS Code 612105.11.H8400
Final Report, June 1976

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Key Words
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Aluminum
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I-Beams
Reinforcing Wires
Hot Isostatic pressing (HIP)
Fabrication

Standard 6061 aluminum I-beams were selectively reinforced on the flanges with single strand T-50 graphite/6061 aluminum composite wire reinforcements by utilizing a hot isostatic pressing (HIP) process. Preliminary mechanical hot pressing trails on graphite-aluminum sandwich construction panels were conducted to investigate the effects of both solid and liquid state processing parameters on composite flexural properties. Mechanical test data on these panels indicated that solid state bonding conditions resulted in higher flexural strength and modulus than liquid state conditions. Based on these results, lay-up and containment was designed to hot isotatically press in the solid state, 0.040'' (0.102 cm.) thick graphite-aluminum layers to the flanges of four standard 6061 aluminum I-beams. Metallographic examination of sections from the HIP processed I-beams showed consolidation had been achieved between the graphite-aluminum composite wires and to the I-beam flange interfaces. However, some sections showed micro-cracks within the composite layers and at the composite layer/I-beam flange interface due to high residual stresses induced during thermal contraction of the I-beam upon cooling from the HIP processing temperature. Consideration of thermal expansion data and relative masses for the T50 graphite/6061 aluminum composite reinforced I-beam support these observations. It was concluded that the process feasibility of selectively reinforcing a standard aluminum I-beam with graphite-aluminum composite layers via hot isostatic pressing was successfully demonstrated. It is recommended that a more moderate modulus fiber such as T300 be considered for the fabrication of selectively reinforced hardware. In addition, design studies directed towards minimizing thermal and mass effects should be conducted on any future work to selectively reinforce structural sections.

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