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BEHAVIOR OF METAL MATRIX COMPOSITE MATERIALS AT CRYOGENIC TEMPERATURES

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FOREWORD

This study of the cryogenic properties of metal matrix composite materials is the result of a Phase II award of the Small Business Innovation Research Program. The work, which studied two discontinuously reinforced composites and graphite reinforced 6061 aluminum made by two different methods, was sponsored by the Naval Surface Warfare Center (NAVSWC), White Oak Laboratory, in Silver Spring, MD.

During the Phase I effort, it was determined that the modulus of elasticity of graphite/aluminum decreased at cryogenic temperatures. While this was attributed to the differences in the coefficients of thermal expansion of the two materials, the mechanism was not understood. This effort fully explained the mechanism as well as the reason for the change in the slope of the modulus line during tensile testing. In addition, data were developed showing the effect of notch severity on the tensile strength of two discontinuous particle strengthened aluminum alloys at various temperatures.

This report summarizes the work performed under NAVSWC Contract Number N60921-88-C-0112. The effort was conducted by Nevada Engineering and Technology Corporation (NETCO), Santa Monica, CA, during the period 18 August 1988 through 18 May 1990.

The NAVSWC technical monitor for this effort, whose help was greatly appreciated, was Albert L. Bertram of the Metallic Materials Branch (Code R32). NETCO's principal investigator was Russell G. Sherman.

Approved by:

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INTRODUCTION

A portion of this Phase II contractual effort was directed at arriving at a better understanding of mechanical testing results on graphite fiber reinforced metal matrix composites (MMC) at cryogenic temperatures. These materials are mixtures of two wholly disparate materials sheathed by another material from which the modulus of elasticity is derived.

The tensile modulus of these structural materials is, in most cases, much more of a concern to designers than is ultimate strength. Service loads rarely exceed 50 percent of the material tensile strength capability, whereas deflection under load is of extreme importance because it has an effect on the structure even at low stresses. It is important to know if the deflection of a structure at any given load level will vary with temperature.

Related to the problem discussed above is the role of the bond strength of the face sheet on the MMC material. Normal tensile testing of these materials is performed by pressure gripping of the tabbed ends of straight-sided specimens. The bond strength of the face sheet on the MMC material is never tested. However, in actual structural components, the load would be transferred by means of adhesives or welding through the face sheet. This problem became evident during the Phase I contract and has been explored further during this Phase II contractual effort.

It is expected that discontinuous MMCs will find wider use than the continuous fiber MMC, but little is known concerning the notch sensitivity of these materials, particularly at cryogenic temperatures. One of these materials, 25 volume percent B_4C/6061, is used in a program at Lockheed Missiles and Space Company (LMSC) for attachment to P100/6061 tubing. This material and another, 25 volume percent SiC/2124, were evaluated as part of this effort.

One of the most important properties of materials being considered for space applications is the ability to withstand alternate heating and cooling. It seems obvious that MMC materials, which are mixtures of two materials with greatly different coefficients of thermal expansion, might show some effect from thermal cycling. During this program, MMC materials were exposed between -320°F and +250°F, thermally cycled for 2000 and 5000 cycles, and then tested for mechanical properties.

A major thrust of this program was to obtain data relative to the LMSC Program on Fundamental Qualification of Graphite/Aluminum Structures.

Before any testing began, a trip was made to LMSC to discuss how this program might develop data helpful to that program. There were two main points which resulted from that meeting. At the time, LMSC intended to use an adhesive for joining the P100/6061 tubing to the B_4C/6061T6 fittings. They recommended Hysol 9394 adhesive for any simulated joint testing. The second point was also a recommendation by LMSC to measure and report any secondary modulus of elasticity.

MATERIALS AND TEST METHODS

The materials tested for this project are listed below.

1. P100/6061 from DWA Composite Specialties 2-ply unidirectional plates. The graphite yarn rolls used wire identified from the "Big Buy" data bank as having a modulus above 110 msi and a strength of approximately 350 ksi. For the purposes of a simple stress analysis invoking rule of mixture, 113 msi was used as the modulus of elasticity of the P100. The coefficient of thermal expansion determined by Nevada Engineering and Technology Corporation (NETCO) was -0.1/°F.

   a. Plate G6139, 42.3 volume percent -.0035 inch face sheets
   b. Plate G6140, 44.2 volume percent -.0035 inch face sheets
   c. Plate G6141, 43.8 volume percent -.0035 inch face sheets
   d. Plate G6142, 45.1 volume percent -.0018 inch face sheets

2. P100/6061 4-inch by 4-feet pultruded plates from Material Concepts, Inc. (MCI), Numbers 1481-122788-03 and 1481-021689-04. The volume percent of this material was reported to be 49 percent prior to cladding with .002 inch of 6061 on each side. The modulus reported using ultrasonics was 57 msi.

3. The B_4C/6061 was supplied by DWA Composite Specialties and was identified as billet No. 2979, reported to be 24.7 volume percent. The billet was extruded to .5-inch by 5-inches and then rolled to .082 inch. The material was supplied in pieces 4-1/2 inches long by 1-inch wide in the T6 condition. The specimens were double disc ground to produce blanks all exactly the same width (approximately .85 inch). All machining after this was by wire Electrical Discharge Machining (EDM). Properties reported by the supplier were:

Direction	Modulus msi	.2% Yield ksi	Ultimate Tensile	Elongation Percent
Longitudinal	15.8	60.2	69.5	2.5
Transverse	15.8	60.5	68.0	2.0

The coefficient of thermal expansion determined by NETCO was 7.7/°F.

4. The SiC/2124 was also supplied by DWA, identified as billet No. 2932, and reported to be 23.1 volume percent. The billet was extruded to 14-inch long by 10.7-inch diameter and then rolled to .085 inch. The material was heat treated to the T4 condition and supplied as 4-1/2-inch long by 1-inch pieces. These were double disc ground to all exactly the same width (approximately .85 inch). All machining after this was by wire EDM. Properties reported by the supplier were:

Direction	Modulus msi	.2% Yield ksi	Ultimate Tensile ksi	Elongation Percent
Longitudinal	16.8	50.1	69.7	3.0
Transverse	16.5	50.6	68.5	3.2

The coefficient of thermal expansion determined by NETCO was 7.8/°F.

Strain gauges on both sides were used for the modulus and yield strength determinations. The P100/6061 specimens were .45-inch wide and were aluminum tabbed. The discontinuous MMCs were tested without tabs.

The thermal cycling was controlled by a Research, Inc., programmer with liquid nitrogen used for cooling and quartz lamps for heating.

Figures 1, 2, and 3 show the nonstandard specimens used to test the particulate materials. Figure 1 shows the wire EDM cracked specimen. The crack represents a stress concentration of approximately 13, which is severe. Figure 2 shows a specimen representing a bolt hole, and the stress concentration is a benign 2.5. Figure 3 is the dogbone specimen used for the smooth bar specimen. Figure 4 shows the single lap shear specimen used to test the face sheet and matrix adhesion strength. All other tests were performed using standard straight sided .45-inch wide tabbed specimens.

RESULTS AND DISCUSSION

This program consisted of four tasks, each one almost entirely independent of the other while at the same time interrelated. These tasks are described below and the discussion will consider them one at a time.

- TASK I was to determine the tensile properties of DWA Composite Specialties P100/6061 from -320°F to 250°F in both the as-fabricated and the T6 condition.
- TASK II was to study the mechanical properties and notch toughness of B_4C/6061T6 and SiC/2124T4 from -320°F to +250°F.
- TASK III was to study the adhesive bond joint strength of B_4C/6061T6 and P100/6061 and to study the face sheet/substrate bond strength of P100/6061 with aluminum face sheets.
- TASK IV was to evaluate the mechanical properties of P100/6061 and B_4C/6061T6 after 2000 and 5000 cycles between -320°F and +250°F.

TASK I

During the Phase I contract, the results indicated that there was a 10 percent decrease in tensile modulus of P100/6061 from room temperature to -315°F. This drop in modulus could be explained on the basis that, due to the 390°F in temperature change, the aluminum contraction would be 0.005 inch per inch. Bonding between the aluminum and graphite would inhibit this contraction, thereby producing a stress greater than the yield strength of the aluminum. With the aluminum in the plastic region, it would contribute only its work hardening modulus instead of its tensile modulus. Based on the rule of mixture, this would account for the 10 percent decrease in modulus.

Heat treating the P100/6061 to the T6 condition increases the tensile strength of the composite because the aluminum makes a greater contribution. Normal 6061T6 has a tensile strength of 45 to 50 ksi. The 6061 in the composite is a cast rather than a wrought product and, therefore, would not be expected to be at that level. The as-fabricated material is not in the T4 (quenched) condition, but it is also more rapidly cooled than the annealed or "O" condition. A good estimate of the strengths in these conditions might be 12 ksi as-fabricated and 32 ksi in the T6 condition. For the yield strength, the levels might be 6 ksi and 22 ksi.

Both the as-fabricated and the T6 condition aluminums should have the same reduced modulus at -315°F. It was initially proposed that the reduced modulus at cryogenic temperatures could be proven by finding that temperature between -315°F and room temperature where the higher yield strength of the T6 condition would result in no drop in modulus because the aluminum would still be in the elastic region.

This method, nice in theory, has some practical problems. The modulus line is traced on an X-Y recorder from the load readout and the strain output of a strain gauge. These lines, obtained from both sides of the specimen, are not always neat and straight but instead sometimes have jags and squibbles, making an exact modulus determination in the initial portion of the curve difficult. The two modulus lines rarely agree and an average must be reported. This difference in moduli might be related to out-of-flat condition or differential residual stresses.

An out-of-flat condition would be expected to distort the initial portion of the load strain curve, and this portion of the curve is generally avoided in determining the modulus. But this is the exact portion of the curve needed if we are looking for a low temperature at which the aluminum is stressed to near the proportional limit and ready to go into the plastic region, thereby dropping the modulus. This problem, of accurately and consistently obtaining a modulus in the initial portion of the curve, precluded the possibility of determining, with any accuracy, the temperatures at which the material in either the as-fabricated or the T6 would not show a decrease in modulus.

This led to another very simple method of proving that the P100/6061, in both conditions, will have a lower modulus at cryogenic temperatures. The P100/6061 would be expected to have a decrease in modulus at -315°F because the differential in the coefficient of thermal expansion of the two materials will cause the aluminum to be at a strain greater than .2 percent. As the specimen is subjected to an increase in stress by the tensile test, the aluminum is in the flow stress or plastic region. If the applied load is removed, the load versus strain line slopes back down along the original elastic modulus line, not the flow stress line. Upon reloading the specimen, the load versus strain line will track back up the elastic modulus until the preload load is reached and then it will break off and resume tracking the flow stress line.

This behavior of unloading parallel to the elastic modulus line is true of all metals which have an elastic modulus. In order to prove this conclusion, specimens were tested at -315°F using a preload of 700 pounds and other specimens at 1000/1100 pounds. In both cases, the preload moduli of the specimens tested at -315°F were lower than the room temperature moduli and, on reloading the moduli, were equal to the room temperature moduli. In both cases, the moduli dropped when the load on the specimens reached the preload.

This indicates that there is the possibility of using a preload process on hardware where it is important to maintain stiffness at cryogenic temperature. The hardware item could be cooled to the expected cryogenic temperature and loaded to the maximum expected load. In service, the aluminum would contribute a 10 by 10^6 psi modulus to the composite even at cryogenic temperatures.

As mentioned in the Introduction, LMSC recommended a change in the modulus measurement technique during the tensile test. Generally, the slope of the modulus line was found to decrease, and this can be attributed to the aluminum reaching the proportional limit. The composite can be considered as two springs, one with a spring constant ten times the other. As the load is applied, the stiffer spring (P100) carries 92 percent of the load and both springs are deflected the same amount. As the load increases, if the spring constant of the smaller spring is exceeded, the larger spring begins to carry more of the load. For the P100/6061 composite at a load equal to half the typical breaking stress, i.e., 60,000 psi on the composite, the P100 carries 92 percent of the load and is 44 percent of the area. This means the P100 is at a stress level of 150 ksi. The aluminum is at a stress level of 10 ksi. In the annealed condition, cast 6061, no doubt, has a proportional limit below 10 ksi. Therefore, it is expected that there will be a change in slope (proportional limit) below 60 ksi in the composite.

This change in slope is entirely dependent on the proportional limit of the 6061. There are no data on the proportional limit of 6061 in any condition; however, in typical load versus strain curves for 6061T6, the proportional limit is generally between 33 ksi and 36 ksi (90 percent of yield). For cast 6061, the proportional limit might be as low as 20 ksi. In the annealed condition, the typical yield strength of 6061 is 8 ksi. The typical proportional limit in the as-cast condition might be 5 to 6 ksi.

There is an additional factor which will lower the proportional limit of the composite. Just as cooling the composite to cryogenic temperatures puts the aluminum in tension, the cooling from the bonding temperatures or the solution treating temperature will also put the aluminum under a tensile stress. This would also have the effect of lowering the proportional limit of the composite.

Tables 1 through 6 contain the results of tensile tests on the P100/6061 in the as-fabricated condition and the T6 condition at room temperature, +250°F, and at -315°F. These tests were all run with a strain gauge on both sides; the specimens were .45-inch wide, between 4 inches and 6 inches in length, and were aluminum tabbed.

The tables list the preload stress, the preload modulus, the re-load modulus, and the secondary modulus. The results of both strain gauges are shown, rather than averaged, because the two results sometimes differ significantly. One of the reasons for this difference could be an out-of-flat condition. In addition to the ultimate strength and total strain to failure, the proportional limit is shown. The proportional limit is the stress at which the load-strain line begins to deviate. This is not always easy to determine because the modulus line is not always a perfectly straight line. Figures 5 and 6 are examples of easy to interpret curves.

In comparing the room temperature properties of the as-fabricated P100/6061 with the T6 condition, several things are obvious. The proportional limit of the T6 material at 72 ksi is double that of the as-fabricated material. This has an effect on the secondary modulus, and the material in the T6 condition has a 10 percent higher secondary modulus. The data show that preloading has no effect on the modulus. The preload modulus and the reload modulus were essentially the same for both materials. The modulus of the T6 material averaged 2 percent higher than the as-fabricated material, but no explanation can be offered for this. The ultimate strength of the T6 material was 9 percent higher, and this is probably due to the fact that aluminum in the T6 condition provides support to the graphite to a higher stress level. A simple stress analysis illustrates how this may operate. For the T6 material, the proportional limit averages 72 ksi. At this stress level the graphite carries 92 percent of the load and is 44 percent the area. The graphite is at a stress level of 150 ksi and the aluminum is at a stress level of 10 ksi. If it is assumed that from this point on the graphite carries 98 percent of the load, at 136 ksi (failure), the additional stress on the graphite is 142.5 ksi for a fracture stress of 293 ksi. For the as-fabricated material, the stress on the graphite at the proportional limit of 35 ksi is 73 ksi. The increased stress on the graphite to 126 ksi (failure) is 202 ksi for a fracture stress of 275 ksi.

The tensile results in Tables 3 and 4 illustrate the effect of low temperature on the modulus of the P100/6061 in both conditions. The preload moduli were both 10 percent lower than the reload first moduli, and the secondary moduli were almost exactly equal to the preload moduli. This is what would be expected. The preload moduli of the as-fabricated material at room temperature and at -315°F are essentially the same, 50.6 msi and 50.8 msi.

The tensile modulus results on the as-fabricated material at -315°F were in excellent agreement with the rule of mixture modulus of 54.3 msi.

In evaluating these data and offering an explanation for the moduli changes due to temperature, it became clear that placing as-fabricated material in a bath of liquid nitrogen for a short period should have the same effect as proof loading. It could be predicted that the aluminum would be stressed beyond the yield strength. Therefore, if the material were brought back to room temperature and tested, the proportional limit would be increased because the aluminum would be in compression. To test out this concept, five additional as-fabricated specimens were placed in liquid nitrogen for one-half an hour and then tested at room temperature. These results (Table 7) show that the prediction was correct. The preload and primary moduli were equal and high and the proportional limit was significantly increased. The ultimate tensile strength was slightly reduced, but this may have no significance because of the small sample size and wide variability of the ultimate strength of this material.

The normal expectation of tensile results, obtained at temperatures above room temperature, is that all the properties, except for ductility, will be reduced. The results from tests on the as-fabricated material at 250°F (Table 5) do not show any change from room temperature results except for the proportional limit. These results were, at first, puzzling because the yield strength of 6061 definitely decreases at 250°F. The increase in proportional limit from 35 ksi at room temperature to 81 ksi at 250°F is due to the compression stress on the aluminum trying to expand. The aluminum is under a compressive stress greater than 20,000 psi, well above its estimated yield strength in the as-fabricated condition. Upon application of the testing load, the aluminum goes from compression to tension, thereby providing a higher proportional limit. In practical terms it means that a P100/6061 structure will be stiffer at high loads at 250°F than at room temperature. It is a little more complex than this because, in a structural application, the load will already have been applied at a cooler temperature so that, as the composite is heated, other changes may be taking place. This could be evaluated by running tests on specimens in a dead load machine or using cantilevered specimens. Both of these techniques would detect movement.

Table 8 lists the averages of all the results shown in Tables 1 through 6. There was no proportional limit at -315°F. The change (decrease) in modulus always occurred at, or near, the preload stress, which is exactly what is expected. The preload modulus and primary moduli were in excellent agreement for all room temperature tests.

TASK II

During the Phase I contractual effort of this program, a 60-degree, V-notch tensile test was run at room temperature and at -315°F on a 30 percent volume SiC_w/6061T6 composite. The results indicated that at room temperature the notch strength decreased 20 percent and at -315°F the notch strength decreased 30 percent.

For the Phase II contractual effort, two different notch severity factors were used; a relatively benign one as would be caused by a bolt hole ($K_t = 2.5$) and a severe one as would be caused by a crack ($K_t = 13$). These specimens are shown in Figures 1 and 2. Wire EDM was used to create the crack and, therefore, the crack had a radius at the tip. The crack was created on both sides in an attempt to create a uniform stress.

Prior to testing the notch specimens, the smooth bar properties of the two MMC materials and commercial 6061T6 were determined at +250°F, room temperature, -150°F, and -315°F. These results are shown in Table 9. The effect of the particulate on aluminum was quite high on the modulus and ultimate strength, increasing them by 50 percent, and on the ductility by decreasing the elongation more than 80 percent. The effect of temperature on these properties is shown in Tables 10, 11, and 12, which give the tensile properties at 250°F, -150°F, and -315°F. The properties at 250°F are marginally affected except for the ductility. These were increased by 50 to 100 percent. At the cryogenic temperature, the tensile strength and moduli of elasticity are increased and the ductility is somewhat decreased. However, it can be concluded that the discontinuous MMC materials have excellent cryogenic properties and both materials were stronger at -315°F than at room temperature.

Data on the notch tensile properties of these materials are shown in Tables 13, 14, and 15. A 1/4-inch hole in a 1-inch wide specimen concentrates the stresses approximately 2.5 times. This has no effect on 6061T6; however, both of these MMC materials suffered a modest 10 percent drop in strength. This indicates that using bolts or rivets to join these materials will provide a relatively safe joint. At cryogenic temperatures, these materials show no increase in notch sensitivity from the benign notch. The results from specimens with the very severe stress concentration, wire EDM cracks, showed that both materials are notch sensitive to severe notches. The SiC/2124T4 material suffered a 30 percent drop in strength, while the B_4C/6061T6 decreased 50 percent. Both materials showed an even larger decrease (37 percent and 60 percent) at -315°F. While the data show that the notch sensitivity increased (for a severe notch) at cryogenic temperatures, of far greater significance is the fact that these materials have little tolerance for cracks at any temperature. The 6061T6 aluminum suffered no loss of notch strength at -315°F.

TASK III

During the Phase I Small Business Innovation Research (SBIR) Program contractual effort, specimens were statically loaded at cryogenic temperatures, room temperature, and at +250°F. Both room temperature and low temperature specimens showed classic three-stage creep. The problem at 250°F was the failure on loading, or within minutes, by face sheet shearing from the P100/6061 substrate. The specimens were loaded by pins through steel tabs which were attached to the specimen by an adhesive. Many failures also occurred in this bond line.

For this Phase II contractual effort, Hysol 9394, a high temperature adhesive, was used following LMSC's advice. Unfortunately, this proved to be a mistake, and every specimen tested at 250°F failed in the adhesive bond line. In order to learn something about the adhesive strength of the metal face sheets to the substrate, room temperature tests were run using a very strong room temperature adhesive. Initially, samples were tested with a tab on each side; however, using a 1-inch overlap, most of the specimens did not fail. Only two specimens failed by shearing of the face sheets and these failed at loads of 1600 pounds and 1660 pounds. Based on a 1-inch overlap and a specimen width of .45, the shear stress (adhesion) of the face sheets is about 1800 psi.

Initially, it seemed that pulling with two tabs would reduce bending and, therefore, provide a truer strength than pulling with one tab. However, the test was made with one tab for two reasons. There was no assurance that both tabs were carrying exactly half the load and, if not, failure of one side would then cause failure of the other side, thereby giving a false low result. The second reason was that, in a practical assembly, the joint would be using only one side in most cases. Specimens were, therefore, fabricated with tabs on one side only. The DWA Composite Specialties material was tested with two different face sheet thicknesses. These plates were G6141 and G6142. The same test was also performed on the MCI material and the results are shown in Table 16. These results indicate that the adhesive strength of the face sheet substrate bond did not appear to be dependent upon the thickness of the face sheet. The face sheet tensile strength at 30,000 psi contributes less than 50 pounds for the .0035-inch face sheet and 25 pounds for the .0018-inch face sheet. The difference in average breaking loads between the two plates with different face sheets was only 130 pounds or 5 percent. It is possible that, with a sufficiently large sample, the thicker face sheet material might be found to be stronger. However, both of the DWA Composite Specialties plates, which averaged 2400 psi shear, were significantly stronger than the MCI material, which was about 2100 psi. This would have to be taken into account in any joining process.

Although the adhesive shear strengths were low, the actual load-to-cause failure is of more importance. The breaking loads were approximately half of the breaking load of the specimen. The overlap was 1 inch, and it is probable that a 2-inch overlap would break at a load somewhat less than double the 1-inch overlap. In any practical joining procedure, it would be necessary to provide sufficient overlap, especially if the joint width did not cover a width equal to the width (or circumference) of the structure. And any joining process, such as welding or brazing which might degrade the interface strength, would have to be evaluated.

TASK IV

The purpose of this task was to determine if these MMC materials would suffer degradation from thermal cycling. Previous tests have been run on materials which had been cycled 250 times. The obvious type of damage would be due to fatigue and, by its nature, fatigue damage requires a great many stress cycles. Therefore, 2000 and 5000 cycles were used. On the cooling side, liquid nitrogen was used, and this meant the specimens were cooled to -315°F. The instrument was programmed to begin counting the cooling cycle when the temperature reached -250°F. The total time below this temperature, both cooling and warming, was 2 minutes. The time at 250°F was 1 minute. The total cycle time was about 7-1/2 minutes with the heat up and cool down time taking 5 minutes.

The original test plan called for testing only DWA Composite Specialties material because this material was thoroughly tested during the other tasks. However, after 2000 cycles, many of the 12-inch long P100/6061 samples were severely distressed. The face sheets were torn at regular increments and the specimens were also twisted. The thermocouple for the heat cycle was not on the surface and, therefore, it is possible that the samples directly exposed to the quartz lamps went to a higher temperature. At this point the thermocouple was repositioned. Samples of the MCI pultruded material were cut to lengths of 1 inch, 2 inches, 4 inches, 8 inches, and 12 inches, and these were placed in the unit for the final 2000 cycles. These samples can be seen in Figure 7. There was no obvious twist in the short samples; however, the 4-, 8-, and 12-inch long samples showed an increasing amount of twist with the 12-inch samples showing almost a 90-degree twist. This could be due to the twist in the graphite yarn or to the graphite not being exactly 0 degrees relative to the longitudinal axis of the specimen. At the time the decision was made to place the MCI pultruded samples in the test, the effect of width was not considered. Interesting data may have been provided if 4-inch long samples by 1-inch and 2-inch widths had been tested.

Figure 8 shows the DWA Composite Specialties' samples after 5000 cycles. The figure shows that this material also twisted, including the 4-inch length samples, and face sheets cracked and peeled on many samples.

An attempt was made to create a bending fatigue specimen by adhesively bonding a 4-1/2-inch length B_4C/6061T6 to a 6-inch long P100/6061 specimen. Twenty of these specimens were placed in the thermal cycle unit but only one survived. In most cases, the adhesive failed. The Hysol 9394 is extremely brittle at low temperatures, and the differential coefficient of thermal expansion between the B_4C/6061 and the P100/6061 caused the complete separation of 18 samples. Figure 9 shows one specimen which did not entirely separate; however, it does shows separation of the bottom face sheet from the substrate and the tearing of the top face sheet. The one specimen that was intact after thermal cycling was permanently bowed. The B_4C/6061 outside surface is in compression (concave) while the P100/6061 outside surface is in tension (convex). The explanation for this may be complex; however, many of the B_4C/6061 samples bowed and, since the B_4C/6061 section size is four times as great as the P100/6061, this more than overcomes the three times stiffer P100/6061.

Figures 10 and 11 show a number of the B_4C/6061 specimens after thermal cycling, and the amount of bow in some of the specimens can be seen. This material was in the T6 condition and, therefore, might have had built-in residual stresses from quenching. How this would cause the part to bow is difficult to explain because merely heating 6061T6 to 250°F will not cause a bow. It is possible that the surface facing the heat source got hotter than the shadow side, expanded more, and retained this greater length. This can only happen with a material having poor thermal conductivity. Since these specimens were only .080-inch thick, there should not be enough of a temperature differential between front and back to cause bowing.

The tensile results obtained on the thermally cycled P100/6061 specimens are shown in Tables 17 through 22, and a summary of all the results comparing the properties to the original material is shown in Table 23.

These results indicate that thermal cycling had little effect on the modulus of the P100/6061 material. There was a slight general degradation of the tensile strength, but most of this can be attributed to warped specimens. Some of the specimens had tensile strengths significantly higher than the uncycled material average. Even if the aluminum matrix had developed fatigue cracks, the aluminum tensile strength contributes little or nothing to the ultimate strength of the composite. Therefore, it could be concluded that thermal cycling can cause degradation by twisting or warping the composite.

The thermal cycling could affect the properties of the B_4C/6061T6 by overaging of the T6 structure. The 5000 cycles represent a minimum of 83 hours at 250°F. MIL-HDBK-5 data indicate that 6061T6 should not show any effect from 100 hours at 250°F. The tensile results of thermally cycled B_4C/6061T6 are shown in Tables 24 through 29, and a summary of all the results is in Table 30. The thermal cycling had a definite effect on the properties. In all cases, the ultimate strength was reduced and there was an increase in ductility. No conclusion can be drawn as to whether or not the increase was commensurate with the decrease in strength. This material should be tested after being soaked for 100 hours at 250°F. This would prove whether or not the material is thermally stable. It is possible that the decrease in strength from thermal cycling was entirely due to overaging, and it is possible that at least some of this overaging came from temperatures over 250°F.

SUMMARY

P100/6061 specimens in the as-fabricated and the T6 conditions were tensile tested at -315°F, room temperature, and 250°F. Some of the specimens were tested by loading them to 30 to 40 percent of the ultimate, unloading, and then reloading. At -315°F, the preload modulus was 10 percent lower than the reload modulus. This is due to the 6061 being at a stress greater than yield strength and, therefore, not contributing the elastic modulus to the composite. During unloading, the load-strain line tracks back down the elastic modulus line and on reloading up to the preload level it tracks back up the elastic modulus line. At this point the load- strain line resumes along the same slope as the preload modulus.

During a room temperature tensile test, there is a decrease in the load versus strain slope, called proportional limit, when the aluminum reaches yield. The proportional limit of the T6 material was twice as high as the as-fabricated condition because heat treating increases the yield strength of 6061. At 250°F, the proportional limit is much higher than at room temperature because the 6061 is in compression at the beginning of the test.

B_4C/6061T6 and SiC/2124T4, both approximately 23 volume percent, were notch tested at the same three temperatures. Three types of specimens were tested: smooth bar, benign notch, and severe notch. Without a notch, both materials had excellent cryogenic tensile properties with an increase in strength at the cryogenic temperatures. Both materials suffered only slight or no loss in strength from a benign notch. Both materials were severely affected by a severe notch and the effect was greater at -315°F.

Single lap shear tests were performed on DWA P100/6061 material of two different thickness face sheets, .0035 inch and .0018 inch, and on MCI rapipressed™ P100/6061 with .002-inch face sheets. The DWA material with the .0035-inch face sheets had a shear strength of 2490 psi, the .00[illegible]3 [illegible]ch face sheet material had a strength of 2360 psi, and the MCI material had a strength [illegible] 085 psi.

P100/6061 and B_4C/6061T6 specimens were cycled between -315°F and 250°F for 2000 and 5000 times. The P100/6061, both MCI and DWA, suffered damage due to warpage. The longer the specimen, the more severe was the damage, which in some cases caused a separation of face sheets. There was a loss of tensile strength which was apparently due to the twist or out-of-flat condition of the specimens. Some of the B_4C/6061 material also warped and suffered a loss in tensile strength. This loss in tensile strength was not due to warpage because only the flattest specimens were tested. The loss in strength was due to overaging, and it is possible that during the heating cycle specimens were heated above 250°F.

CONCLUSIONS

1. P100/6061 in the as-fabricated and in the T6 condition has 10 percent lower modulus at -315°F than at room temperature.

2. This reduction in modulus is due to the aluminum being at a stress greater than its yield strength so that the aluminum contribution to the modulus is significantly reduced.

3. The change in modulus exhibited by P100/6061 during tensile testing (proportional limit) is due to the aluminum being stressed beyond its yield strength.

4. P100/6061T6 has a higher proportional limit than the as- fabricated material because heat treating 6061 significantly increases the yield strength.

5. The P100/6061 has a significantly higher proportional limit at 250°F than at room temperature because the aluminum is under a severe compression stress during the initial portion of the test.

6. Thermal cycling P100/6061 between -315°F and 250°F for 2000 cycles degraded the material due to twisting or warping of the material. This distress is significant on lengths of 8 inches or more.

7. The bond strength between the 6061 face sheets and the P100/6061 matrix can be determined by the use of a single lap shear test. The shear strength of DWA material is about 2400 psi while rapipressed™ MCI material has a shear strength of 2100 psi.

8. Both B_4C/6061T6 and SiC/2124T4 have a low notch tensile ratio in the presence of a severe notch. The SiC/2124T4 has a notch tensile ratio of .71 while the B_4C/6061T6 was .5. With a relatively benign notch, such as a bolt hole, both materials have a notch tensile ratio of .9 at room temperature.

9. Both B_4C/6061T6 and SiC/2124T4 have excellent smooth bar cryogenic properties but show increased notch sensitivity in the presence of a severe notch at -315°F.

10. Thermal cycling between -315°F and 250°F for 2000 and 5000 cycles reduced the tensile strength of B_4C/6061T6. This reduction seemed to be due to overaging and not embrittlement.

RECOMMENDATIONS

1. The effect of width on the warpage and twisting of P100/6061T6 during thermal cycling should be determined.

2. The effect of 100 hours and 1000 hours at 250°F on P100/6061 and B_4C/6061T6 should be determined. At this temperature, the aluminum in the P100/6061 is under severe compression and should show the effects of creep.

3. Tests should be run on dead loaded P100/6061 which is alternately heated and cooled while under stress.

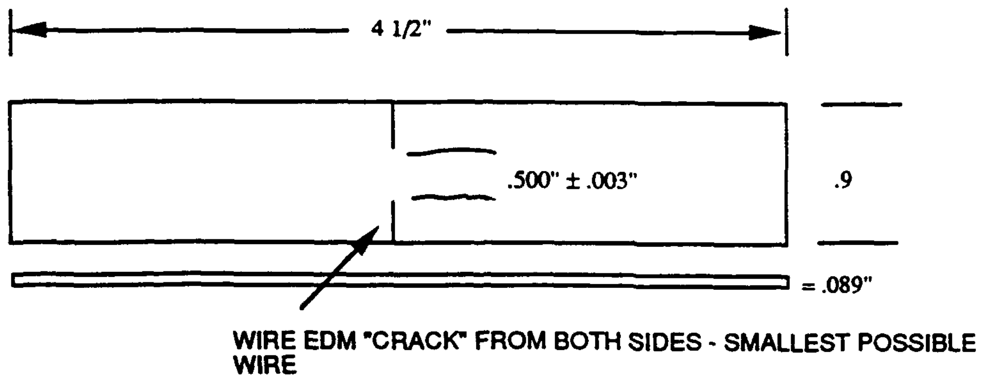

FIGURE 1. WIRE EDM CRACKED SPECIMEN USING .004-INCH DIAMETER WIRE (STRESS CONCENTRATION EQUALS 13)

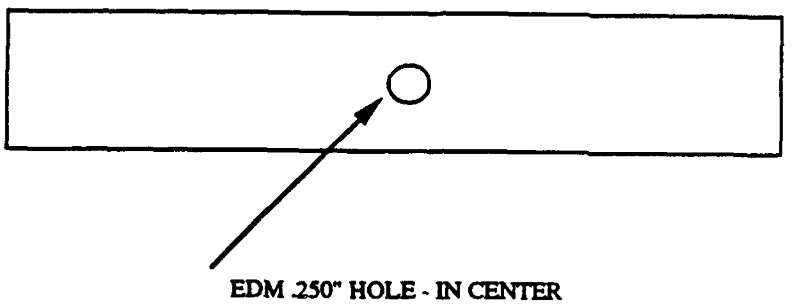

FIGURE 2. BOLT HOME SIMULATED SPECIMEN (STRESS CONCENTRATION EQUALS 2.5)

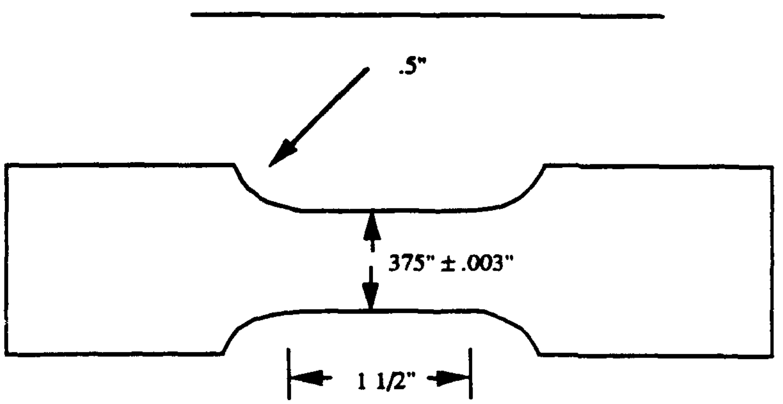

FIGURE 3. DOGBONE SPECIMEN FOR SMOOTH BAR PROPERTIES

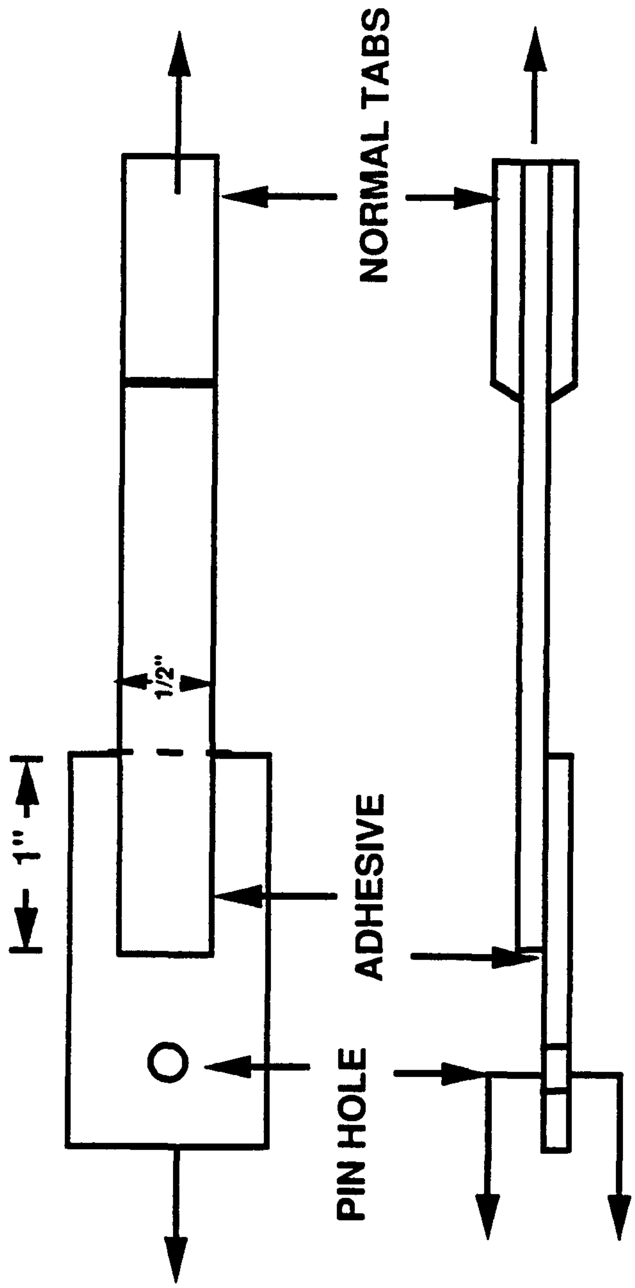

FIGURE 4. FACE SHEET ADHESION TEST

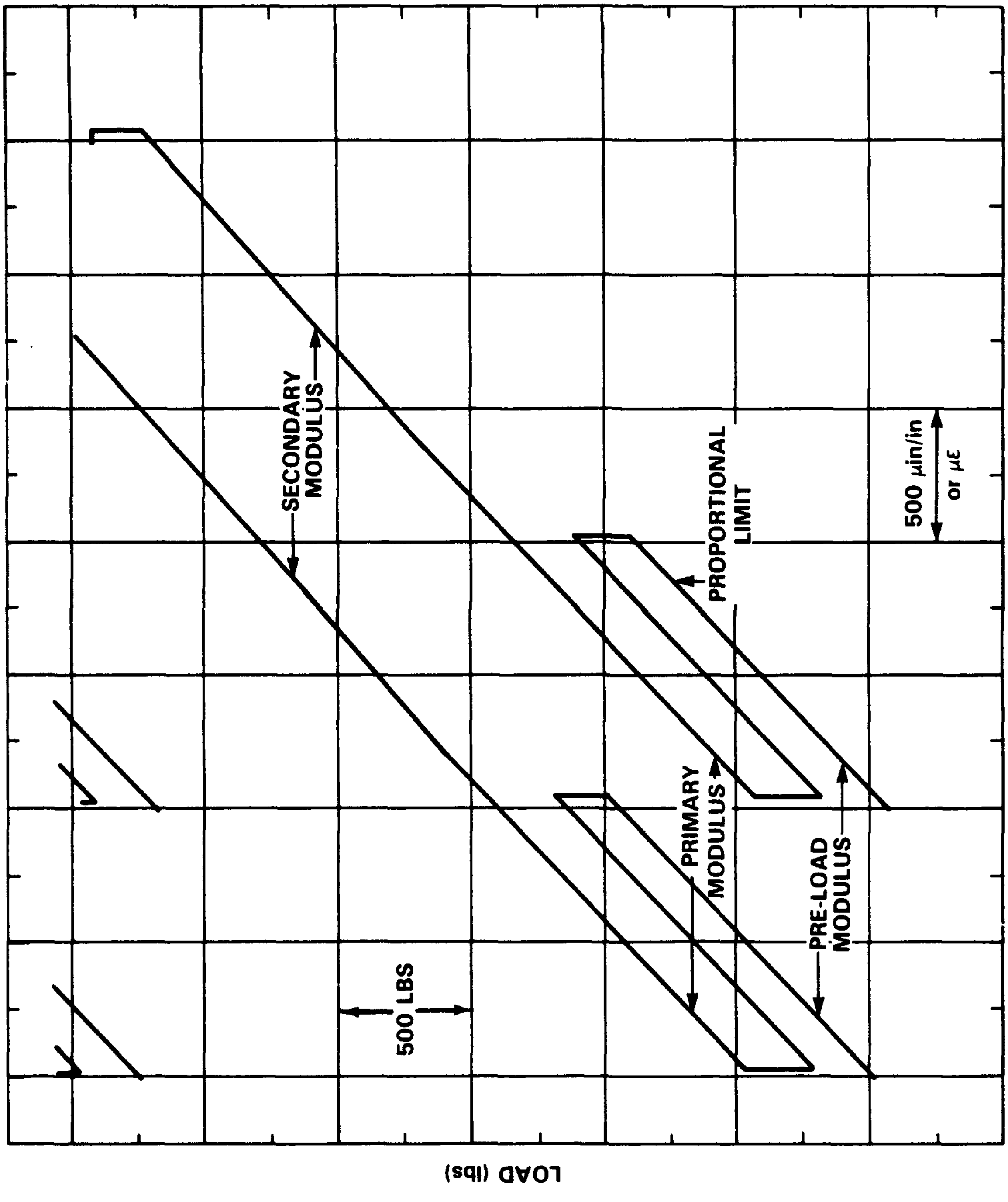

FIGURE 5. LOAD-STRAIN CURVES FROM BOTH SIDES OF SPECIMEN 38 P100/6061 TENSILE TESTED ROOM TEMPERATURE

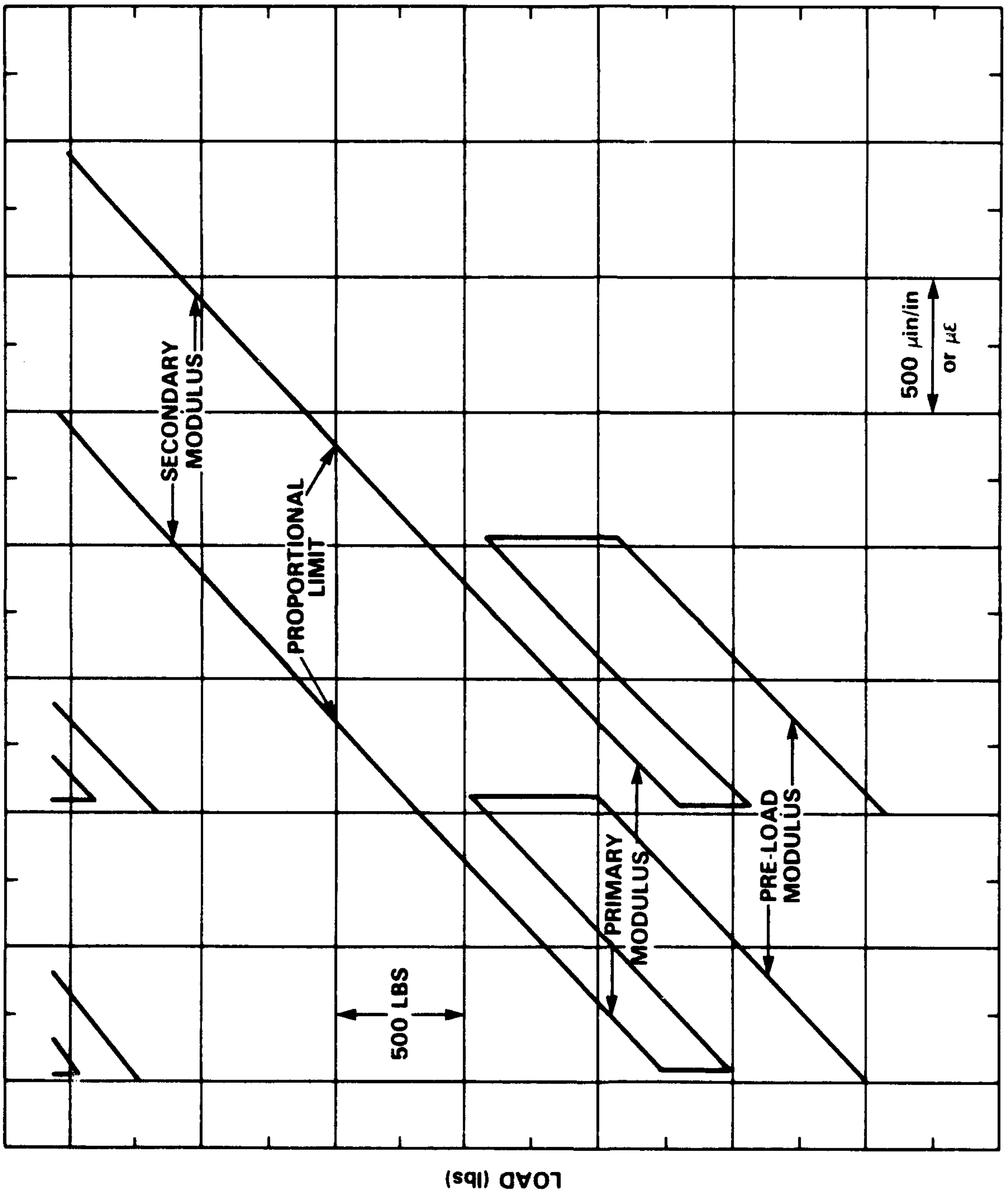

FIGURE 6. LOAD-STRAIN CURVES FROM BOTH SIDES OF SPECIMEN 45 P100/6061 TENSILE TESTED ROOM TEMPERATURE

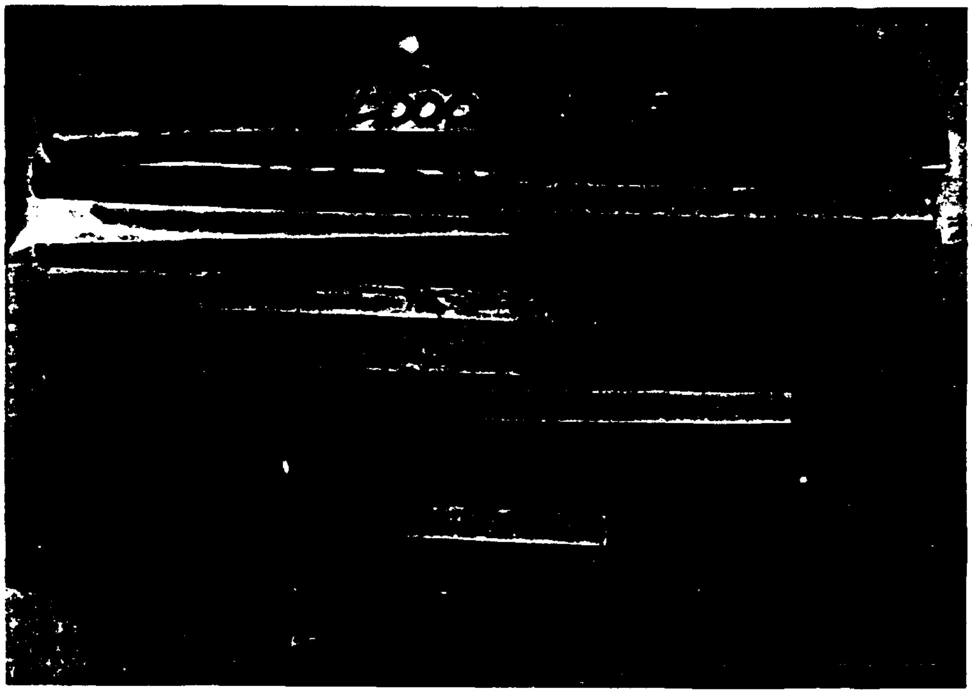

FIGURE 7. MCI PULTRUDED P100/6061 SAMPLES OF VARIOUS LENGTHS AFTER 2000 THERMAL CYCLES BETWEEN -315°F AND 250°F

FIGURE 8. DWA P100/6061 SAMPLE AFTER 5000 THERMAL CYCLES BETWEEN -315°F AND 250°F

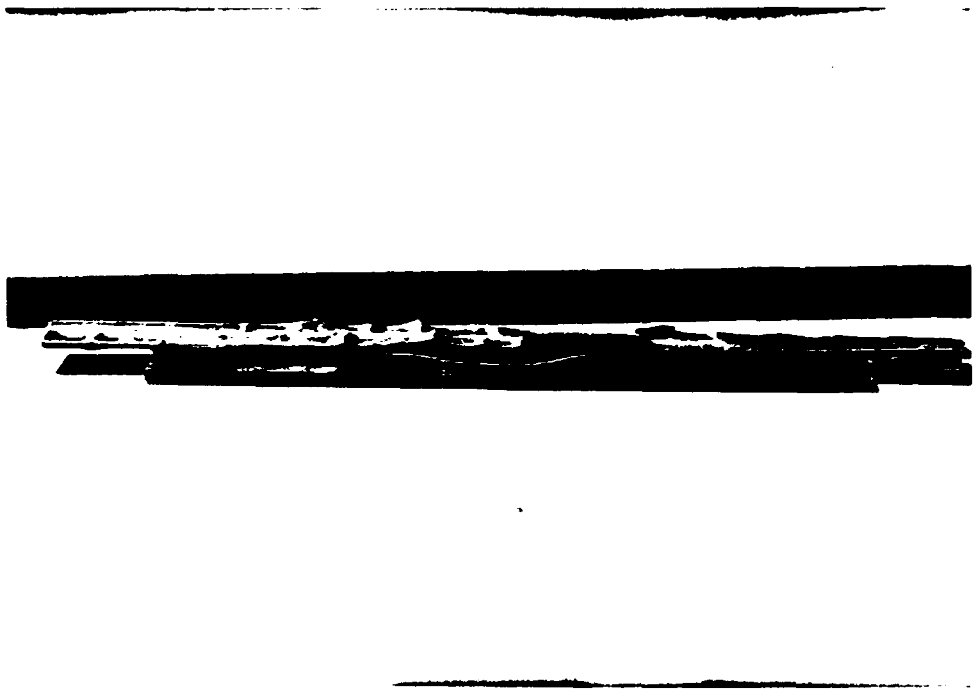

FIGURE 9. B_4C/6061T6 ADHESIVE BONDED TO P100/6061 AND THERMALLY CYCLED 5000 TIMES BETWEEN -315°F AND 250°F

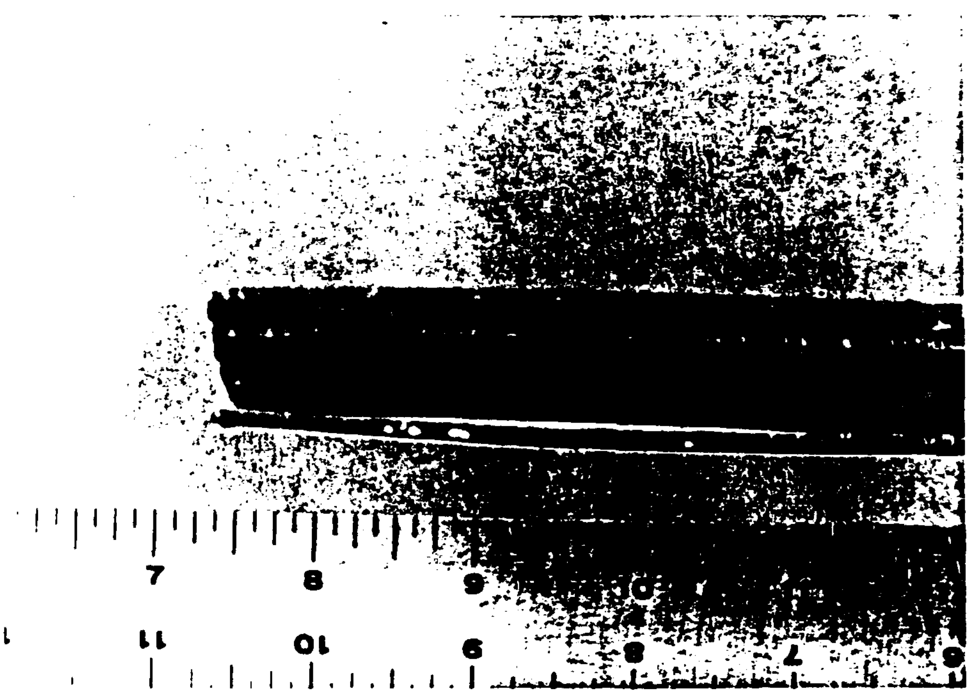

FIGURE 10. B_4C/6061T6 AFTER 5000 THERMAL CYCLES BETWEEN -315°F AND 250°F

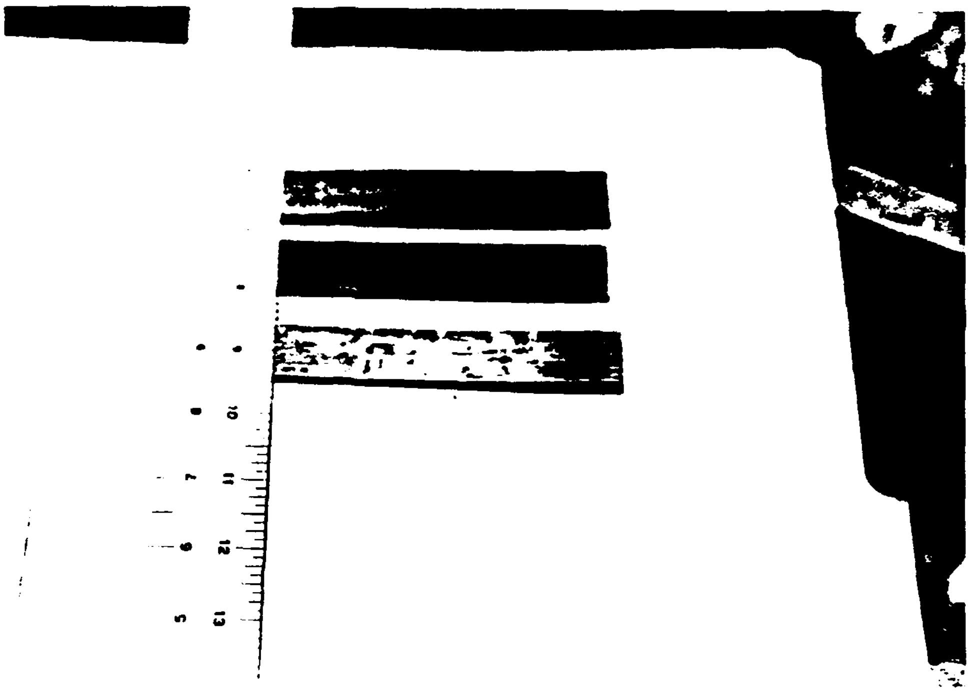

FIGURE 11. B_4C/6061T6 AFTER 5000 THERMAL CYCLES BETWEEN -315°F AND 250°F

TABLE 1. TENSILE PROPERTIES OF P100/6061T6 AT ROOM TEMPERATURE

SPECIMEN	PRELOAD STRESS ksi	PRELOAD MODULUS msi	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
16	Not Done	--	52.4(1)	49.8	92.6	143.1	.29
			51.7(1)	51.7	66.7		
10	Not Done	--	57.1(1)	51.3	40.8	148.0	.29
			51.1(1)	50.7	88.0		
69	58	52.1	52.4	49.2	73.3	132.3	.27
		51.7	53.0	50.8	71.7		
45	56	51.7	51.7	49.8	70.4	132.1	.27
		53.2	52.8	50.8	66.3		
67	55	49.6	50.9	48.4	69.4	144.3	.30
		50.9	52.7	48.6	63.9		
18	44.5	52.8	52.2	52.6	82.0	123.0	.24
		53.0	53.5	51.9	56.0		
20	43	50.9	51.8	49.1	66.4	129.3	.25
		51.2	51.4	49.1	64.8		
17	44	55.5	55.3	52.8	62.7	140.6.28	
		50.3	50.8	47.2	122.0		
AVERAGE		52.2	52.4	50.3	72.3	136.5	

(1) Averaged with Preload Modulus

TABLE 2. TENSILE PROPERTIES OF AS-FABRICATED P100/6061 AT ROOM TEMPERATURE

SPECIMEN	PRELOAD STRESS ksi	PRELOAD MODULUS msi	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
21	Not Done	--	49.5(1)	46.8	40.0	123.9	.26
			52.7(1)	46.1	29.3		
19	Not Done	--	53.0(1)	48.9	43.3	128.4	.26
			51.9(1)	49.1	36.3		
38	58.5	50.3	52.5	48.1	43.5	136.9	.28
		52.4	52.9	48.2	43.5		
43	52.5	52.4	52.5	48.6	44.2	132.4	.27
		51.9	52.4	47.3	42.6		
28	56.5	48.9	50.3	45.1	40.3	115.6	.25
		48.9	50.0	45.3	40.3		
4	43.0	48.9	49.0	44.9	20.2	121.0	.26
		49.0	50.6	45.7	29.6		
7	46.0	52.3	52.8	47.0	24.2	129.5	.27
		50.3	51.8	46.2	29.2		
13	41.0	48.0	49.4	44.0	28.4	117.1	.26
		49.4	48.9	43.0	30.4		
AVERAGE		50.6	51.1	46.5	35.3	125.6	

(1) Averaged with Preload Modulus

TABLE 3. TENSILE PROPERTIES OF P100/6061T6 AT -350°F

SPECIMEN	PRELOAD STRESS ksi	PRELOAD MODULUS msi	PRIMARY MODULUS msi	SECONDARY MODULUS msi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
22	Not Done	--	46.9(1) 46.4	None	140.1	.35
24	Not Done	--	45.5(1) 44.7	None	119.2	.26
52	39	53.1 43.2	60.9 48.5	49.6 44.6	136.8	.29
58	37	52.3 46.4	60.8 52.1	49.6 48.8	138.1	.28
25	61.5	46.5 46.0	51.2 51.2	47.7 49.4	127.9	.27
42	45.5	55.0 45.0	56.7 52.5	49.3 49.0		
32	44	48.6(2)	48.9	None	141.9	.29
33	49	48.2 47.7	51.2 54.1	45.2 49.2	136.8	.28
36	45	49.1 49.1	48.3 52.1	43.3 49.3	142.3	.27
37	56	51.8 51.8	54.2 56.5	51.5 49.5	137.0	.25
40	59	50.6 46.5	55.0 52.2	49.6 49.2	125.0	.24
29	57	53.1 46.9	60.4 52.2	51.4 48.2	137.9	.26
AVERAGE		48.5	53.6	48.6	133.7	

(1) Values Used for Preload Modulus

(2) Only One Strain Gage

TABLE 4. TENSILE PROPERTIES OF P100/6061 AS FABRICATED AT -350°F

SPECIMEN	PRELOAD STRESS ksi	PRELOAD MODULUS msi	PRIMARY MODULUS msi	SECONDARY MODULUS msi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
58	65	51.2 49.1	56.1 52.1	49.5 50.2	133.6	.26
66	41	56.9 44.1	64.4 47.8	51.6 47.8	123.5	.24
30	42	51.6 47.6	56.9 52.5	48.8 48.6	144.9	.29
35	42	45.8 55.4	53.1 53.1	49.2 48.9	133.7	.27
31	50	47.0(1)	51.7	48.7	132.2	.27
46	44	46.6 62.3	49.9 67.3	47.6 53.2	127.7	.23
73	44	64.9 44.9	64.4 52.4	52.4 42.3	142.4	.28
44	55	46.6 53.4	N/A N/A	49.5 51.4	143.7	.28
65	57	49.9 54.4	53.9 57.8	49.9 51.6	131.4	.28
70	49	N/A N/A	55.9 53.9	49.0 45.5	148.9	.28
62	Not Done	Not Done	46.1(2) 52.5	N/A	133.6	.24
23	Not Done	Not Done	46.4(2) 50.9	N/A 46.2	132.4	.27
AVERAGE		50.8	55.5	49.1	135.7	

N/A-Not Available
(1)-Only One Strain Gage
(2)-Values Used for Proof Load Modulus

TABLE 5. TENSILE PROPERTIES OF AS-FABRICATED P100/6061 AT 250°F

SPECIMEN GROUP 5-2	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE STRENGTH ksi	STRAIN TO FAILURE %
3	54.5	51.6	72.3	109.9	.22
	53.2	50.3	72.2		
5	55.1	50.8	74.2		.24
	53.9	48.7	84.8	119.2	
6	54.1	49.4	75.4	125.0	.25
	55.0	50.4	67.3		
11	54.8	49.4	99.7	122.7	.24
	53.4	48.5	104.8		
12	59.3	55.3	68.0	131.0	.24
	57.1	52.5	92.4		
AVERAGE	55.0	50.7	81.1	121.6	

TABLE 6. TENSILE PROPERTIES OF AS-FABRICATED P100/6061T6 AT 250°F

SPECIMEN GROUP 5-2	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE STRENGTH ksi	STRAIN TO FAILURE %
2	57.1	55.6	80.0	122.6	.23
	53.3	52.0	82.9		
6	51.1	51.1	110.1	110.1	.22
	53.9	52.9	76.8		
8	53.9	52.2	68.2	121.4	.24
	53.5	51.8	66.1		
14	51.2	48.3	58.3	113.5	.23
	49.9	49.2	93.9		
15	54.4	50.8	54.6	126.3	.26
	50.8	49.2	85.6		
AVERAGE	52.9	51.3	77.7	118.8	

TABLE 7. ROOM TEMPERATURE TENSILE PROPERTIES OF P100/6061 AS-FABRICATED AFTER A 30-MINUTE SOAK AT -320°F

SPECIMEN GROUP 5-1	PRELOAD[1] MODULUS msi	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
50	51.0	51.2	51.2	N/A	134.6	.27
	50.2	50.2	50.2	N/A		
54	55.7	55.3	54.3	106.0	116.6	.22
	55.9	55.7	52.1	79.5		
63	54.0	53.8	52.1	93.3	101.6	.20
	54.9	54.9	51.2	65.9		
68	53.1	53.9	51.1	85.0	127.8	.26
	55.8	55.2	51.1	71.3		
71	50.8	51.3	48.7	85.3	123.2	.25
	54.4	52.3	50.6	61.3		
AVERAGE	53.6	53.4	51.3	81.0	120.8	

(1) All specimens were preloaded to 49 ksi.

TABLE 8. AVERAGE TEST RESULTS FOR TENSILE TESTS ON P100/6061 IN THE AS-FABRICATED CONDITION AND T6 CONDITION AT ROOM TEMPERATURE, -315°F AND 250°F

CONDITION	TEMP. °F	PRELOAD MODULUS msi	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi
As-Fabricated	RT	50.6	51.1	46.5	35.3	125.6
T6	RT	52.2	52.4	50.3	72.3	136.5
As-Fabricated	-315	50.8	55.5	49.2	N/A	135.7
T6	-315	48.5	53.6	48.8	N/A	133.8
As-Fabricated	250	Not Done	55.0	50.7	81.1	121.6
T6	250	Not Done	52.9	51.3	77.7	118.8
As-Fabricated Cryo Soaked at -315°F for 1/2 hour	RT	53.6	53.5	51.4	81.0	120.8

TABLE 9. TENSILE PROPERTIES OF COMMERCIAL 6061T6, 25 VOLUME PERCENT SiC/2124T4 AND 25 VOLUME PERCENT B_4C/6061T6 AT ROOM TEMPERATURE

MATERIAL SPECIMEN NUMBER	MODULUS OF ELASTICITY msi	2 % YIELD STRENGTH ksi	ULTIMATE TENSILE ksi	ELONGATION 1 INCH %
6061T6				
1	10.3	N/A	48.1	15
	9.4			
2	10.0	N/A	48.6	16
	9.6			
3	10.4	41.6	48.4	16.5
	9.6			
SIC/2124T4				
26	14.5	N/A	70.3	2.5
	15.1			
27	15.0	N/A	61.0	2
	14.2			
28	14.7	48.5	75.5	N/A
	14.5			
B_4C/6061T6				
26	15.2	N/A	63.4	2
	15.8			
27	14.3	N/A	66.7	2
	16.7			
28	17.2	53.8	63.9	2.5
	14.5			

TABLE 10. TENSILE PROPERTIES OF COMMERCIAL 6061T6, 25 VOLUME PERCENT SiC/2124T4 AND 25 VOLUME PERCENT B_4C/6061T6 AT 250°F

MATERIAL SPECIMEN NUMBER	MODULUS OF ELASTICITY msi	2 % YIELD STRENGTH ksi	ULTIMATE TENSILE ksi	ELONGATION 1 INCH %
6061T6				
7	9.6	40.5	46.0	15.5
	9.8			
8	9.8	40.3	45.9	15.5
	9.6			
9	9.7	40.3	45.9	15.5
	9.6			
SiC/2124T4				
32	14.4	49.4	70.6	4
	14.6			
33	14.1	49.1	73.6	5
	14.8			
34	15.6	49.2	73.6	4.5
	13.7			
B_4C/6061T6				
32	15.9	51.1	60.2	2.5
	14.2			
33	14.5	51.6	61.6	3
	15.1			
34	14.6	51.9	61.0	3
	15.0			

TABLE 11. TENSILE PROPERTIES OF COMMERCIAL 6061T6, 25 VOLUME PERCENT SiC/2124T4 AND 25 VOLUME PERCENT B_4C/6061T6 AT 150°F

MATERIAL SPECIMEN NUMBER	MODULUS OF ELASTICITY msi	2 % YIELD STRENGTH ksi	ULTIMATE TENSILE ksi	ELONGATION 1 INCH %
6061T6				
10	10.3	42.5	50.0	15
	11.1			
11	10.0	43.6	50.8	13
	10.3			
12	10.0	41.2	52.0	15
	10.8			
SiC/2124T4				
35	14.8	47.8	78.0	3.5
	15.0			
36	14.9	47.0	68.6	2
	16.0			
37	16.0	46.2	64.3	1.5
	16.1			
B_4C/6061T6				
35	15.1	60.1	68.5	1
	16.9			
36	14.8	55.1	69.1	2
	16.2			
37	15.5	56.4	68.2	2
	14.9			

TABLE 12. TENSILE PROPERTIES OF COMMERCIAL 6061T6, 25 VOLUME PERCENT SiC/2124T4 AND 25 VOLUME PERCENT B_4C/6061T6 AT -315°F

MATERIAL SPECIMEN NUMBER	MODULUS OF ELASTICITY msi	2 % YIELD STRENGTH ksi	ULTIMATE TENSILE ksi	ELONGATION 1 INCH %
6061T6				
4	11.0	48.0	59.6	16.5
	12.2			
5	10.7	45.1	56.6	14.5
	11.7			
6	11.4	47.3	58.1	15
	N/A			
SiC/2124T4				
29	16.3	56.4	79.5	1.5
	N/A			
30	16.7	57.1	65.0	1
	16.0			
31	15.2	56.3	79.0	1.5
	16.9			
B_4C/6061T6				
29	16.4	NONE	74.8	1
	17.1			
30	19.1	NONE	74.9	1.5
	14.0			
31	15.6	NONE	75.1	1
	17.0			

TABLE 13. NOTCH TENSILE PROPERTIES OF COMMERCIAL 6061T6, SiC/2124T4 AND B_4C/6061T6 AT ROOM TEMPERATURE

MATERIAL	SPECIMEN	ULTIMATE TENSILE ksi	NOTCH TENSILE RATIO
6061T6	NO NOTCH*	48.3*	
6061T6	HOLE K_t = 2.5	48.9	
6061T6	HOLE K_t = 2.5	48.5	1.0
6061T6	HOLE K_t = 2.5	48.4	
SIC/2124T4	NO NOTCH*	68.9*	
SIC/2124T4	HOLE K_t = 2.5	67.0	
SIC/2124T4	HOLE K_t = 2.5	67.2	.92
SIC/2124T4	HOLE K_t = 2.5	55.3	
B_4C/6061T6	NO NOTCH*	64.7*	
B_4C/6061T6	HOLE K_t = 2.5	59.4	
B_4C/6061T6	HOLE K_t = 2.5	59.6	.90
B_4C/6061T6	HOLE K_t = 2.5	56.0	
6061T6	WIRE EDM	49.8	
6061T6	CRACK $K_t \approx 13$	50.0	1.03
6061T6		49.9	
SIC/2124T4	WIRE EDM	49.6	
SIC/2124T4	CRACK $K_t \approx 13$	49.8	.71
SIC/2124T4		47.1	
B_4C/6061T6	WIRE EDM	33.9	
B_4C/6061T6	CRACK $K_t \approx 13$	33.6	.50
B_4C/6061T6		30.0	

* Average from Table 7

TABLE 14. NOTCH TENSILE PROPERTIES OF COMMERCIAL 6061T6, SiC/2124T4 AND B_4C/6061T6 AT 250°F

MATERIAL	SPECIMEN	ULTIMATE TENSILE ksi	NOTCH TENSILE RATIO
6061T6	NO NOTCH*	46*	
6061T6	HOLE K_t = 2.5	46.8	
6061T6	HOLE K_t = 2.5	48.1	1.04
6061T6	HOLE K_t = 2.5	48.0	
SIC/2124T4	NO NOTCH*	72.6*	
SIC/2124T4	HOLE K_t = 2.5	67.0	
SIC/2124T4	HOLE K_t = 2.5	67.2	.92
SIC/2124T4	HOLE K_t = 2.5	67.0	
B_4C/6061T6	NO NOTCH*	60.9*	
B_4C/6061T6	HOLE K_t = 2.5	59.1	
B_4C/6061T6	HOLE K_t = 2.5	56.7	.95
B_4C/6061T6	HOLE K_t = 2.5	57.2	
6061T6	WIRE EDM	48.2	
6061T6	CRACK $K_t \approx 13$	48.1	1.05
6061T6	CRACK $K_t \approx 13$	48.1	
SIC/2124T4	WIRE EDM	51.0	
SIC/2124T4	CRACK $K_t \approx 13$	51.3	.69
SIC/2124T4	CRACK $K_t \approx 13$	48.2	
B_4C/6061T6	WIRE EDM	28.0	
B_4C/6061T6	CRACK $K_t \approx 13$	33.6	.50
B_4C/6061T6	CRACK $K_t \approx 13$	30.4	

*Average from Table 8

TABLE 15. NOTCH TENSILE PROPERTIES OF COMMERCIAL 6061T6, SiC/2124T4 AND B_4C/6061T6 AT -315°F

MATERIAL	SPECIMEN	ULTIMATE TENSILE ksi	NOTCH TENSILE RATIO
6061T6	NO NOTCH*	58.1*	
6061T6	HOLE K_t = 2.5	62.9	
6061T6	HOLE K_t = 2.5	62.4	1.08
6061T6	HOLE K_t = 2.5	62.3	
SIC/2124T4	NO NOTCH*	74.5*	
SIC/2124T4	HOLE K_t = 2.5	72.7	
SIC/2124T4	HOLE K_t = 2.5	80.3	1.03
SIC/2124T4	HOLE K_t = 2.5	77.2	
B_4C/6061T6	NO NOTCH*	74.9*	
B_4C/6061T6	HOLE K_t = 2.5	62.8	
B_4C/6061T6	HOLE K_t = 2.5	72.1	.91
B_4C/6061T6	HOLE K_t = 2.5	68.5	
6061T6	WIRE EDM	60.9	
6061T6	CRACK $K_t \approx 13$	59.2	1.04
6061T6	CRACK $K_t \approx 13$	60.4	
SIC/2124T4	WIRE EDM	46.0	
SIC/2124T4	CRACK $K_t \approx 13$	48.1	.63
SIC/2124T4	CRACK $K_t \approx 13$	47.1	
B_4C/6061T6	WIRE EDM	31.3	
B_4C/6061T6	CRACK $K_t \approx 13$	28.2	.41
B_4C/6061T6	CRACK $K_t \approx 13$	33.0	

*Average from Table 10

TABLE 16. FACE SHEET ADHESION TO SUBSTRATE TEST RESULTS ON DWA AND MCI P100/6061 AS-FABRICATED

SPECIMEN	BREAKING LOAD POUNDS	SHEAR STRENGTH ksi	AVERAGE ksi
G6141 (.0035 Inch Face Sheet)			
1	1190	2616	
2	940	2091	
3	1285	2843	2491
4	1140	2437	
5	1060	2368	
G6142 (.0018 Inch Face Sheet)			
1	1020	2312	
2	1050	2254	
3	1040	2309	2357
4	1200	2565	
5	1085	2345	
MCI			
1	900	2067	
2	1020	2328	
3	940	2072	2085
4	920	2039	
5	900	1920	
13-3 (T6 Condition)	670	1473	

TABLE 17. ROOM TEMPERATURE TENSILE PROPERTIES OF P100/6061 AS-FABRICATED AFTER 2000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 1-1	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
1	56.8[1] (48.4) 59.5 (50.6)	55.5 (47.3) 59.5 (50.6)	25.2 None	110.6	.22
2	50.4 55.8	45.9 54.0	94.1 24.6	135.0	.27
3	48.7 47.5	46.2 45.3	31.4 47.6	102.9	.24
4	51.0 50.0	46.1 46.7	53.8 40.3	109.4	.25
5	54.6 49.5	54.6 49.5	None None	138.4	.24
AVERAGE	50.7	48.6	45.3	119.3	

(1) This specimen had no aluminum face sheets. Values in parentheses are normalized to give values had face sheets been present.

TABLE 18. ROOM TEMPERATURE TENSILE PROPERTIES OF P100/6061 AS-FABRICATED AFTER 5000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 2-1	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
1	51.4 55.3	51.4 52.2	None 21.8	137.6	.27
2	50.1 51.1	50.1 50.1	None 93.6	128.7	.26
3	48.6 55.2	45.6 52.0	95.7 67.4	107.4	.22
4	54.[illegible] 45.2	49.7 43.2	64.9 71.4	112.3	.25
5	47.4 50.5	45.4 47.9	17.7 22.6	114.4	.26
AVERAGE	50.9	48.8	56.9	120.0	

TABLE 19. TENSILE PROPERTIES AT -315°F OF P100/6061 AS-FABRICATED AFTER 2000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 1-3	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
11	51.1 55.0	51.1 52.1	None 26.0	111.0	.22
12	49.5 47.2	47.2 45.1	25.8 18.3	104.4	.23
13	52.0 45.0	47.3 42.9	14.7 18.9	99.5	.22
14	47.7 46.8	46.4 44.3	20.9 49.2	110.0	.26
15	45.4* 44.4	None	None	77.3*	.18
AVERAGE	49.3	46.9	24.8	106.2	

* This specimen was twisted. Values not used in average.

TABLE 20. TENSILE PROPERTIES AT -315°F OF P100/6061 AS-FABRICATED AFTER 5000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 1-3	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
11	49.8	42.7	25.5	133.3	.27
	47.9	51.0	47.7		
12	48.9	45.5	60.4	121.4	.26
	47.8	43.9	88.5		
13	48.0	44.4	28.2	66.1*	.15
	42.5	45.5	42.2		
14	44.0	46.9	50.3	125.7	.26
	51.6	47.7	23.5		
15	46.1	45.9	45.2	108.8	.23
	47.4	46.1	45.2		
AVERAGE	47.5	46.0	45.7	122.3	

* Not Used in Average.

TABLE 21. TENSILE PROPERTIES AT 250°F OF P100/6061 AS-FABRICATED AFTER 2000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 1-2	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
6	50.0 54.7	41.4 46.9	58.5 50.6	94.5	.24
7	50.2 53.6	47.8 50.7	40.2 42.9	108.6	.23
8	66.9 67.2	63.0 62.6	52.2 68.7	115.5	.19
9	69.0 67.7	66.6 65.2	62.5 78.4	146.4	.22
10	55.5 54.8	51.2 52.0	49.3 52.0	104.0	.20
AVERAGE	59.0 (53.1)*	54.7 (48.3)*	55.5	113.8	

*Averages without above rule of mixture values of Number 8 and Number 9.

TABLE 22. TENSILE PROPERTIES AT 250°F OF P100/6061 AS-FABRICATED AFTER 5000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 1-2	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
6	53.1	48.6	24.4	99.6	.22
	47.5	42.4	62.7		
7	50.2	44.5	63.2	98.3	.22
	50.2	43.7	66.4		
8	62.2	58.0	26.2	98.1	.18
	51.4	56.5	38.1		
9	54.3	49.3	66.4	121.0	.22
	57.0	53.0	27.8		
10	Too severely warped to be tested *				
AVERAGE	53.2	49.5	46.9	116.0	

* All specimens were at least slightly warped.

TABLE 23. SUMMARY OF TENSILE PROPERTIES OF OF P100/6061 AS-FABRICATED AFTER THERMAL CYCLING BETWEEN 250°F AND -315°F

CONDITION	TEST TEMPERATURE °F	PRIMARY MODULUS msi	SECONDARY MODULUS msi	PROPORTIONAL LIMIT ksi	ULTIMATE TENSILE ksi
Not Cycled	RT	50.6	46.5	35.3	125.6
2000 Cycles	RT	50.7	48.6	45.3	119.3
5000 Cycles	RT	50.9	48.8	56.9	120.0
Not Cycled	250	55.0	50.7	81.1	121.6
2000 Cycles	250	53.1	48.3	55.5	113.8
5000 Cycles	250	53.2	49.5	46.9	116.0
Not Cycled	-315	50.8	49.2	57.8*	135.7
2000 Cycles	-315	49.3	46.9	24.8	106.2
5000 Cycles	-315	47.5	46.0	45.7	122.3

* Most of these specimens were preloaded which had the effect of changing the proportional limit.

TABLE 24. ROOM TEMPERATURE TENSILE PROPERTIES OF B_4C/6061T6 AFTER 2000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 3-1	MODULUS msi	2% YIELD ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
1	15.2 15.2	N/A	63.7	1.1
2	13.9 17.1	N/A	61.0	0.9
3	13.8 15.1	55.5	62.5	1.8
4	15.0 14.7	16.7	27.7	5.6
5	16.2*	35.5	44.7	3.3
AVERAGE	15.1		51.9 (62.6)(1)	2.5 (1.3)(1)

* Only One Strain Gage
(1) Average of First Three

TABLE 25. ROOM TEMPERATURE TENSILE PROPERTIES OF B_4C/6061T6 AFTER 5000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 4-1	MODULUS msi	2% YIELD ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
1	12.2 15.2	31.2	36.5	1.2
2	15.0 15.0	34.9	43.3	1.9
3	13.7 15.8	53.5	59.9	2.2
4	13.5 15.8	N/A	30.8	6.1
5	13.0 18.9	N/A	62.8	1.8
AVERAGE	14.7		46.7	2.6

TABLE 26. TENSILE PROPERTIES OF B_4C/6061T6 AT 250°F AFTER 2000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 3-2	MODULUS msi	2% YIELD ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
6	15.3 16.0	50.4	61.0	1.4
7	14.9 18.1	20.3	30.6	6.7
8	15.0 15.0	55.0	59.2	1.2
9	15.4 14.9	55.7	62.1	1.6
10	15.0 12.5	16.3	27.6	8.6
AVERAGE	15.2		48.1 (60.8)(1)	3.9 (1.4)(1)

(1) Average of Numbers 6, 8, and 9.

TABLE 27. TENSILE PROPERTIES OF B_4C/6061T6 AT 250°F AFTER 5000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 4-2	MODULUS msi	2% YIELD ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
6	14.5 15.5	18.3	29.2	8.6
7	12.7 14.6	16.8	24.8	7.2
8	15.3 18.2	46.1	51.7	2.9
9	13.6 15.5	39.0	46.2	2.3
10	20.4 21.6	32.8	39.9	3.5
AVERAGE	16.2		38.4	4.9

TABLE 28. TENSILE PROPERTIES OF B_4C/6061T6 AT -315°F AFTER 2000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 3-3	MODULUS msi	2% YIELD ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
11	17.7 15.9	37.7	59.3	0.8
12	13.6 13.3	20.5	47.8	2.6
13	N/A	13.8	34.8	2.9
14	13.4 13.9	40.8	56.3	0.8
15	12.5 17.9	19.0	49.6	2.3
AVERAGE	14.8		49.6	2.5

TABLE 29. TENSILE PROPERTIES OF B_4C/6061T6 AT -315°F AFTER 5000 CYCLES HEATING TO 250°F AND COOLING TO -315°F

SPECIMEN GROUP 4-3	MODULUS msi	2% YIELD ksi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
11	17.0 13.6	*	35.6	4.3
12	13.5 15.1		49.8	1.0
13	16.4 22.1		82.1	.9
14	11.2 12.8		32.9	2.8
15	15.3 13.7		43.2	1.7
AVERAGE	15.1		48.7	2.1

* All Strain Gage Adhesion Failed before Yield.

TABLE 30. SUMMARY OF TENSILE PROPERTIES OF B_4C/6061T6 AFTER THERMAL CYCLING BETWEEN 250°F AND -315°F

CONDITION	TEST TEMPERATURE °F	MODULUS msi	ULTIMATE TENSILE ksi	STRAIN TO FAILURE %
Not Cycled	RT	15.6	64.7	2.2
2000 Cycles	RT	15.1	51.9	2.5
5000 Cycles	RT	14.7	46.7	2.6
Not Cycled	250	14.9	60.9	2.8
2000 Cycles	250	15.2	48.1	3.9
5000 Cycles	250	16.2	38.4	4.9
Not Cycled	-315	16.5	74.9	1.2
2000 Cycles	-315	14.8	49.6	2.5
5000 Cycles	-315	15.1	48.7	2.1

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This report lists the results of mechanical tests, specifically ultimate strength, modulus of elasticity, strain-to-failure, and proportional limit, of graphite P100/6061, 25 volume percent SiC/2024, and 25 volume percent B_4C/6061 at -300°F, room temperature, and 250°F. The latter two were evaluated using notch specimens. These results showed that the B_4C/6061 was severely damaged by a notch and that the SiC/6061 was only moderately damaged; however, the notch tensile at -300°F was only slightly lower than that at 70°F. The only effect of thermal cycling between 300°F and 250°F was from overaging. The Gr/6061, on the other hand, was severely damaged due to warpage and face sheet cracking. The modulus of the Gr/6061 is reduced at -300°F because the 6061 is stressed beyond the yield strength and contributes little to the modulus of the composite.

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