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FABRICATION OF ANGLEPLY CARBON-ALUMINUM COMPOSITES

by

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East Hartford, Connecticut

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16. Abstract

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ABSTRACT

A study was conducted to fabricate and test angleply composites consisting of NASA-Hough carbon base monofilament in a matrix of 2024 aluminum. The effect of fabrication variables on the tensile properties of $[(\pm 45)/(0)_4/(\mp 45)]_T$ was determined, and an optimum set of conditions was established. The size of the composite panels was successfully scaled up, and the material was tested to measure tensile behavior as a function of temperature, stress-rupture and creep characteristics at two elevated temperatures, bending fatigue behavior, resistance to thermal cycling, and Izod impact response.

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Fabrication of Angleply Carbon-Aluminum Composites

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I. INTRODUCTION

Under Contract NAS3-15704, "Fabrication of Aluminum-Carbon Composites", (Ref. 1) techniques were developed for the preparation of unidirectional carbon-base monofilament/aluminum alloy composites. It was found that such composites exhibited good translation of longitudinal filament properties, and good retention of these properties at test temperatures up to 427°C under both short term and long term (100 hrs) testing. In addition the composites demonstrated resistance to thermal aging and thermal cycling.

As a logical extension of this work, the subject program was sponsored by NASA-Lewis in order to examine the fabricability and measure the properties of monofilament carbon-aluminum composites having a ply configuration typical of that which might be used in an actual application. The application selected was a gas turbine engine fan blade, which requires a combination of high bending and torsional stiffnesses, light weight, and resistance to elevated temperature.

The objectives of this program were to develop optimum fabrication techniques for angleply carbon-aluminum composites and to measure the critical mechanical properties of the resultant material. The materials to be investigated were carbon base monofilament having a diameter of .0081 and .0142 cm (3.2 and 5.6 mils) in a 2024 aluminum alloy matrix. Fabrication techniques were based on those developed under contract NAS3-15704, and resultant composites were evaluated for tensile, stress-rupture, fatigue, thermal cycling, and impact behavior.

The program was divided into six tasks as outlined below:

Task I - Characterization of Uniaxial Composites
Task II - Fabrication Development of Angleply Composites
Task III - Size Scale-up and Process Optimization
Task IV - Fabrication and Characterization of Angleply Composites
Task V - Fabrication of Panels for Delivery to NASA-Lewis
Task VI - Reports.

The following sections of this report describe the work conducted during each of the four technical tasks.

II. MATERIALS

The reinforcement utilized throughout the program was NASA-Hough carbon base monofilament supplied by NASA-Lewis. The filament is produced by a chemical vapor deposition of both carbon and boron onto a carbon monofilament substrate to form an alloy consisting of approximately 73 wt % C and 27 wt % B. Two sizes of monofilament were evaluated. The one most extensively studied was the same as that utilized in the previous contract, and had a diameter of .0081 cm - .0086 cm (3.2 mils - 3.4 mils). The modulus of elasticity of this filament was measured to be 198 GN/m^2 (28.8 msi) (Ref. 1).

Two batches of this monofilament were received in the course of the program, and both were extensively evaluated by tensile testing to determine the filament's strength characteristics. All testing was conducted using a 2.54 cm (1 in.) gage length. Figures 1 and 2 are histograms of shipments 1 and 2, respectively. The data indicate that the first batch, which consisted of spools 4 and 5, was somewhat better than the second batch which consisted of spools 1, 1000, 1010, and 1020. The first batch had a higher average, a lower standard deviation and a much larger percentage of filament with a strength in excess of 2.07 GN/m^2 (300 ksi).

Figure 3 is a histogram of all the 3.2 mil filament data, including shipments 1 and 2. The average UTS and standard deviation were nearly identical to those measured on similar filament in Ref. 1.

The strengths of the 5.6 mil filament are plotted in Fig. 4. Although the average was higher for the larger diameter filament, the standard deviation was also higher, and this would be expected to have a detrimental effect on composite strength. A limited number of modulus measurements was made on the large filament, and the average of five tests was 221 GN/m^2 (32 msi) which was significantly higher than that of the 3.2 mil filament.

Another difference in the two filaments is evident in Fig. 5. The 3.2 mil monofilament is produced in a multiple stage reactor (Ref. 2) which apparently creates the series of rings which can be seen in the top photomicrograph. No such rings can be seen in the 5.6 mil filament, indicating that a different procedure was used in its production. A further indication of different procedures in making the two filaments is the presence of a distinct ring at the interface between the core and the deposit in the 5.6 mil filament. This is probably due to a reaction at the surface of the core during the vapor deposition process. No reaction zone is evident in the smaller diameter filament.

The matrix material utilized throughout the program was 2024 aluminum alloy in both foil and -400 mesh powder form.

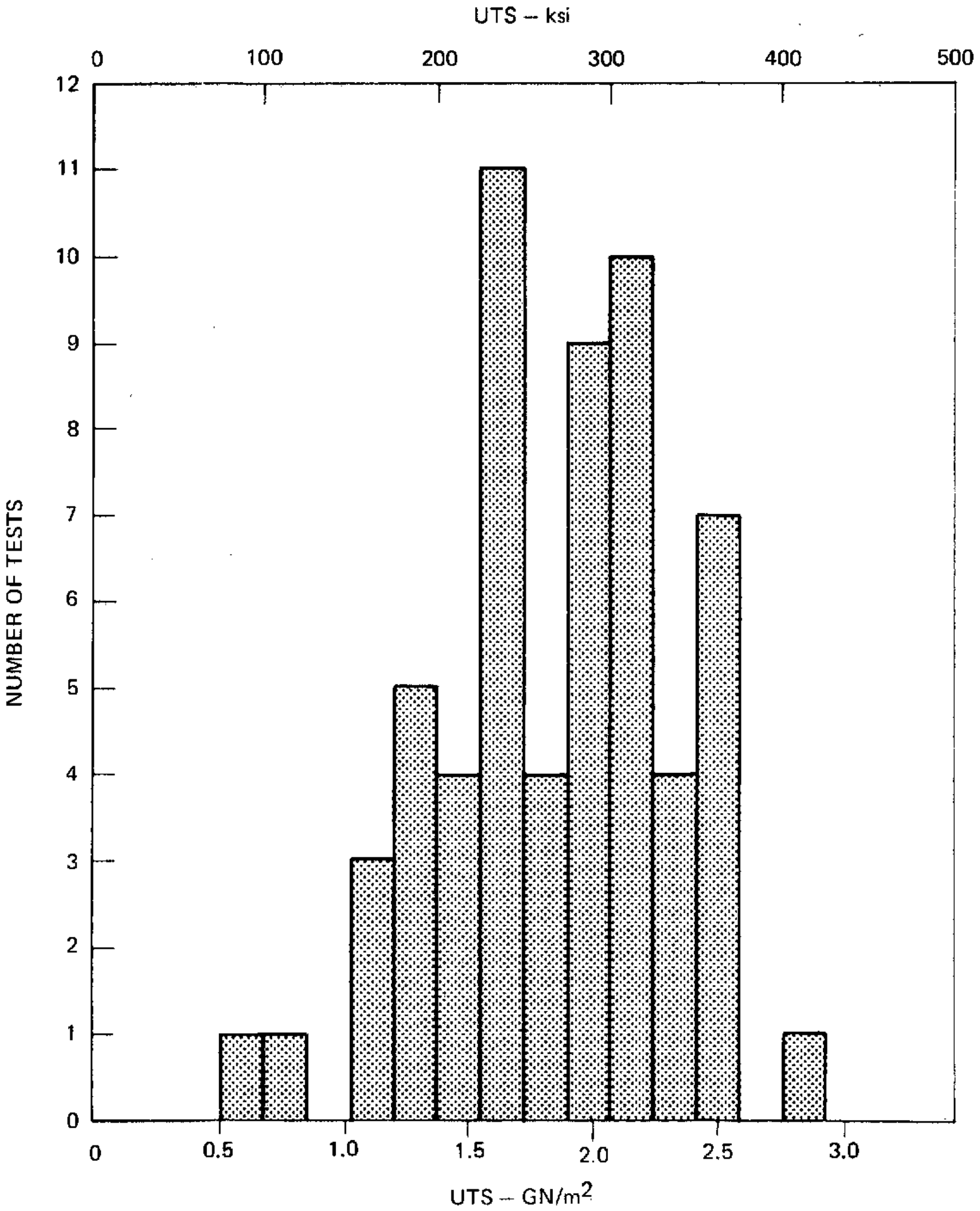
FIG. 1

3.2 MIL NASA–HOUGH CARBON BASE MONOFILAMENT

SHIPMENT 1

AVERAGE UTS 1.86 GN/m^2 (270 ksi)

STD. DEV. 0.46 GN/m^2 (67 ksi)



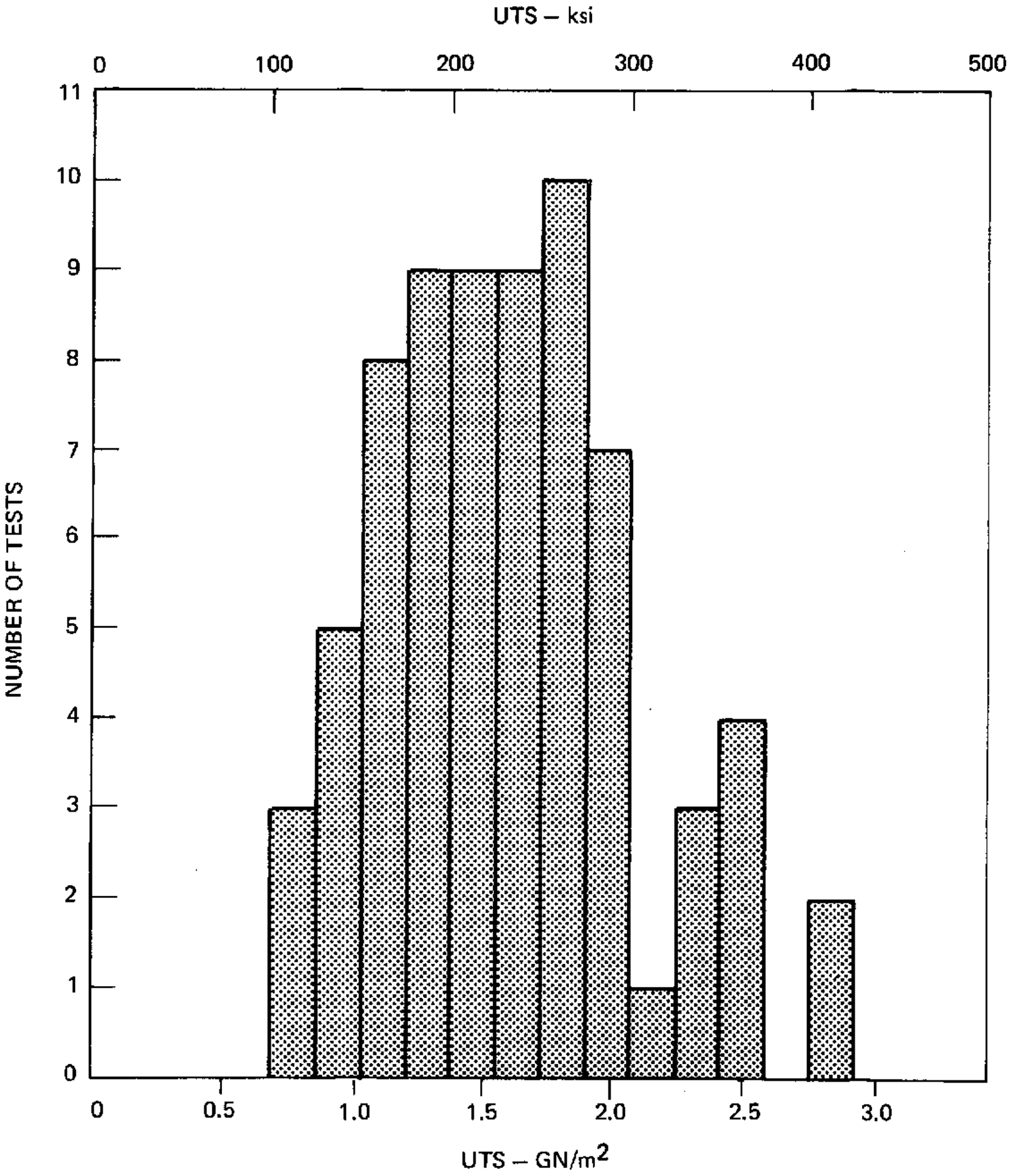
N06–83–1

3.2 MIL NASA–HOUGH CARBON BASE MONOFILAMENT

SHIPMENT 2

AVERAGE UTS 1.61 GN/m^2 (233 ksi)

STD. DEV. 0.49 GN/m^2 (71 ksi)



3.2 MIL NASA–HOUGH CARBON BASE MONOFILAMENT

SHIPMENTS 1 AND 2

AVERAGE UTS 1.72 GN/m^2 (249 ksi)

STD. DEV. 0.51 GN/m^2 (74 ksi)

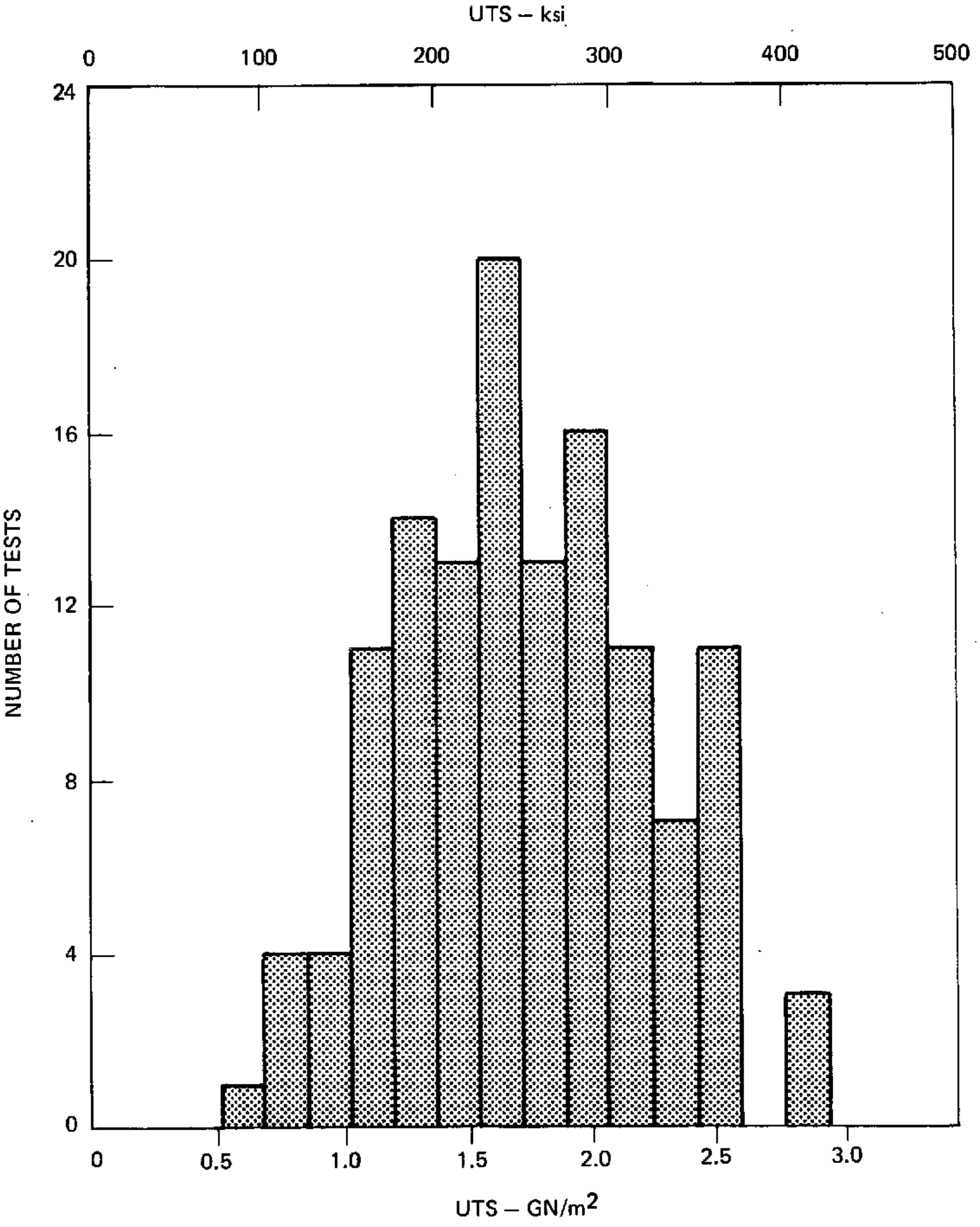
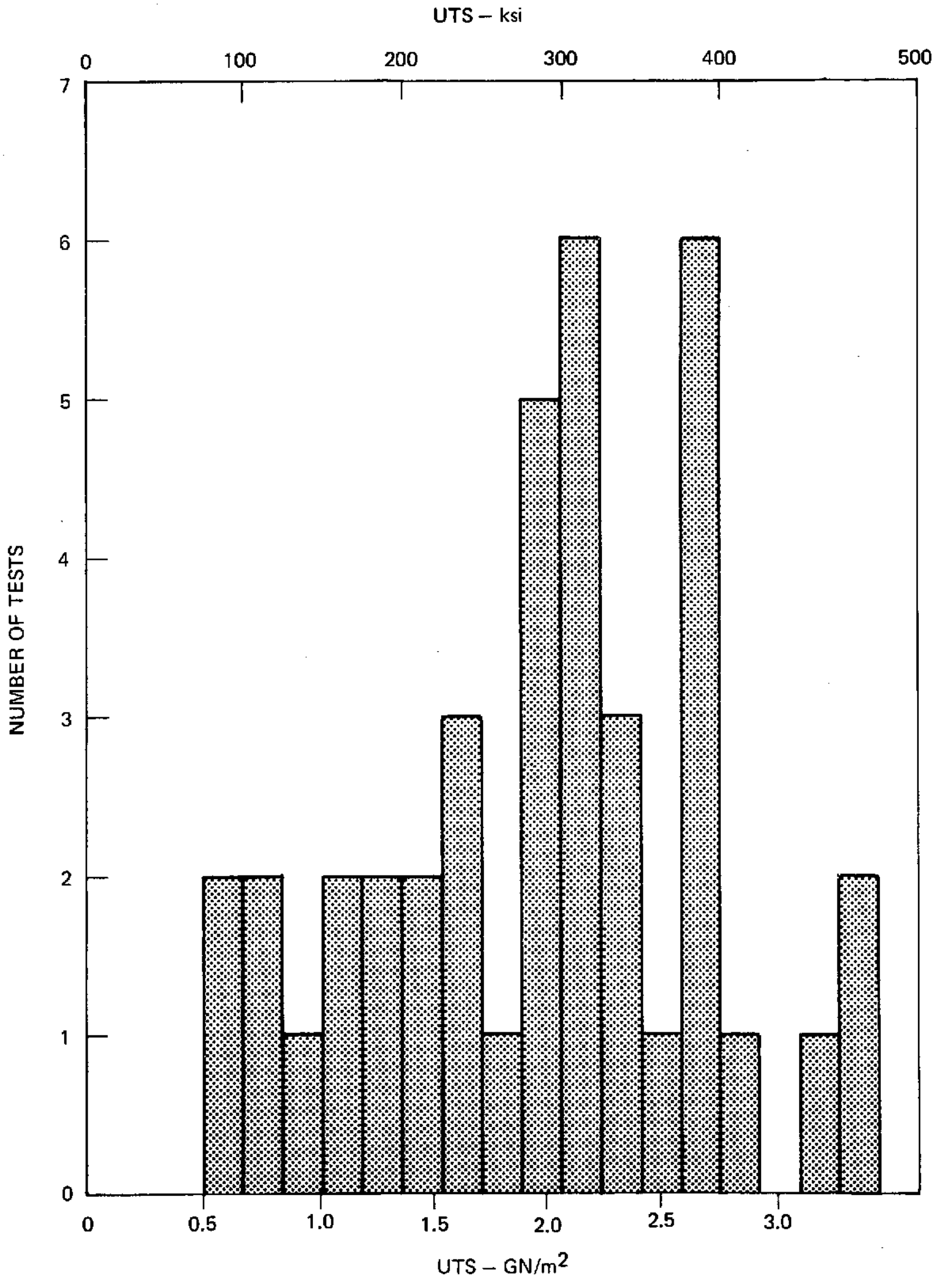


FIG. 4

5.6 MIL NASA–HOUGH CARBON BASE MONOFILAMENT

AVERAGE UTS 1.97 GN/m^2 (286 ksi)

STD. DEV. 0.72 GN/m^2 (104 ksi)



NASA–HOUGH CARBON BASE MONOFILAMENTS

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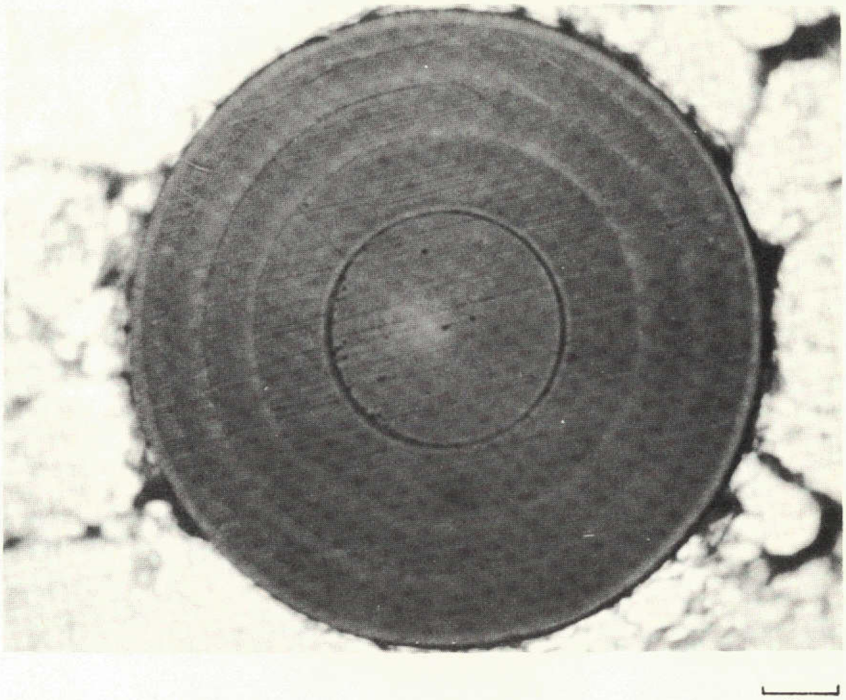
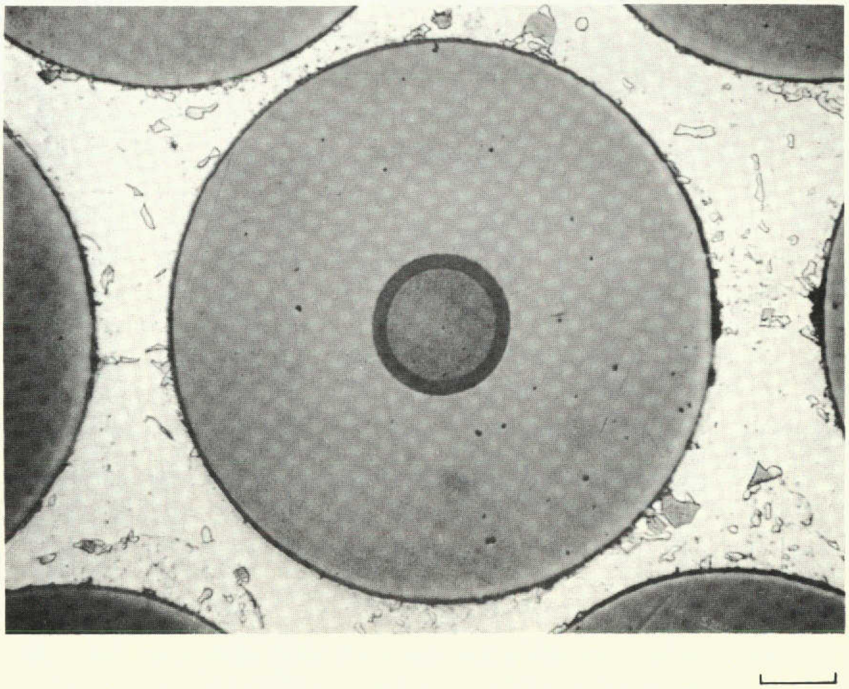


3.2 MIL FILAMENT



5.6 MIL FILAMENT

III. TASK I - CHARACTERIZATION OF UNIAXIAL COMPOSITES

Filament received in the initial portion of the program (spools 4 and 7) was processed into precursor tape by the plasma spray process described in Ref. 1. Spool 4 was 0.0081 cm (3.2 mil) NASA-Hough monofilament, while spool 7 was 0.0142 cm (5.6 mil) in diameter. Two panels were fabricated from the tape having the 0.0081 cm fiber. The first (2114) was hot pressed under 69 MN/m^2 (10 ksi) at 450°C for 30 min while No. 2121 was pressed under 138 MN/m^2 (20 ksi) at 450°C for 30 min. Composite 2115 which was reinforced with the 0.0142 cm filament was fabricated under the same conditions as composite 2114. The results of the tests are presented below in Table I.

Table I

Longitudinal Tensile Data
Uniaxial NASA-Hough/2024 Aluminum Composites

No.	Fiber Dia. cm	Fiber Vol %	UTS GN/m^2	UTS (ksi)	Modulus GN/m^2	Modulus (msi)	Failure Strain %
2114-1	0.0081	46	0.683	99	130	18.9	0.75
-2		49	0.835	121	143	20.8	0.86
-3		52	0.759	110	-	-	0.75
2121-1	0.0081	53	0.772	112	133	19.3	0.76
-2		49	0.772	112	124	18.0	0.84
-3		50	0.745	108	134	19.5	0.75
2115-1	0.0142	50	0.841	122	145	21.0	0.88
-2		51	1.12	163	178	25.8	0.88
-3		51	0.855	124	163	23.6	0.87

The strengths of both the composites reinforced with the smaller diameter filament (Nos. 2114 and 2121) were similar to those measured in the previous contract. The different pressures used in fabrication of the composites did not seem to have an effect on their strength. The moduli were somewhat higher than those measured previously; the average of the current tests being 133 GN/m^2 (19.3 msi) vs 109 GN/m^2 (15.8 msi) for the data in Ref. 1. The moduli of the larger diameter filament composites were even higher, reflecting the higher filament modulus. The strength of these specimens was also quite good with the value of 1.12 GN/m^2 (163 ksi) being higher than any measured under the previous program. These results indicated an excellent translation of the larger diameter filament properties. In addition, its size facilitated fabrication and handling of the precursor tape and could lead to more easily achieving high fiber volume fractions and uniform fiber distributions in composites.

The conclusions drawn from this task were (1) that the 0.0081 cm (3.2 mil) diameter filament was essentially equivalent to that utilized under contract NAS3-15704 insofar as handling, composite fabrication, and composite tensile properties were concerned, and (2) that the larger diameter monofilament was somewhat easier to handle due to its higher breaking load, and the higher filament modulus was translated into the composite.

IV. TASK II - FABRICATION DEVELOPMENT OF ANGLEPLY COMPOSITES

The objective of this task was to develop the techniques to fabricate small angleply composites. The primary means of evaluating the effects of fabrication variables was the measurement of the longitudinal tensile strength of the composites. The angleply configuration selected for study consisted of eight layers in a core-shell construction as follows: $[(\pm 45)/(0)_4/(\mp 45)]_T$. This is typical of the laminates used in gas turbine engine blading applications, and possesses a good combination of bending and torsional stiffness.

4.1 Experimental Procedure

The same sequence of events which was used in the preparation and consolidation of precursor tapes for uniaxial composites was utilized for angleply composites. Precursor tape was prepared by drum winding the filament over 2024 aluminum foil followed by the application of additional aluminum in powder form. Three techniques were evaluated for applying the additional aluminum: plasma spray (the method used in NAS3-15704), slurry coating, and aerosol spray. In the plasma spray process the filament was drum wound then passed by a plasma spray torch under controlled rotation and traverse speeds to produce a uniform coating of plasma sprayed aluminum powder on the tape. The amount of aluminum deposited was controlled through the powder feed rate, drum speed, and number of passes. The slurry process consisted of winding filament on the foil covered drum then brushing on a slurry of aluminum powder to fill the interstices between the filaments. The slurry contained 60g 2024 powder (-400 mesh), 4g polystyrene, and 196 ml toluene. The brushing was repeated until the desired amount of powder was deposited.

As a result of difficulties experienced during the program with these techniques, a third method was developed for depositing aluminum powder on the drum wound tape using an aerosol spray. Prior to the application of the powder, the process was identical to the plasma spray and slurry processes. The NASA-Hough monofilament was wound on a foil-covered drum at prescribed spacing. The powder was then made into a dilute slurry in the following proportions:

2024 powder (-400 mesh)	90g
xylene	150g
polystyrene	10g

The small particle size was deemed necessary in order to minimize clogging of the sprayer nozzle. A technique was developed wherein a uniform deposit having the same aerial density as the plasma spray could be sprayed on the aluminum foil.

All precursor tapes were consolidated into composites by hot pressing under an argon atmosphere at a temperature below the solidus of the aluminum alloy (diffusion bonding). Composite dimensions were nominally 7.6 cm x 2.54 cm x .089 cm (3 in. x 1 in. x .035 in.).

The primary means of evaluating the effect of the fabrication variables was a composite tensile test which was conducted on a straight sided specimen, 7.6 cm x 1.27 cm x .089 cm (3 in. x 1/2 in. x .035 in.) Aluminum doublers were adhesively bonded to both ends of the specimen leaving a 2.54 cm (1 in.) gage length. All tests were conducted at a crosshead speed of 0.0254 cm/min (0.01 in./min). Specimen elongation was measured using two strain gages, one being bonded to each side to eliminate bending effects.

4.2 Results and Discussion

An initial precursor tape was made from spool No. 4 using the plasma spray process utilized during contract NAS3-15704. It was found quite difficult to cut the 45° plies due to a tendency for the fibers to lift from the foil and separate from each other. This problem had been encountered under the previous contract but was not as troublesome because the plies were all unidirectional. In order to reduce the lifting, a solution of polystyrene dissolved in toluene was painted on the tape to adhere it to the foil backing. This improved the handleability somewhat, but several fibers remained poorly aligned.

As a result of these difficulties the composites were not of as good a quality as would be desired. The strength properties and the fabrication conditions are listed in Table II. Based on the data it appeared that the 103 MN/m^2 (15 ksi) pressure resulted in low strengths, most likely due to fiber breakage. It should be noted that even higher pressure did not result in any degradation in strength of unidirectional composite 2121 tested in Task I (see Table I). However, breakage is much more likely with the fiber crossovers in the angleply construction. This may be reflected in the data which showed that the best strengths were achieved with the lowest fabrication pressure (34 MN/m^2) when the time of pressurization was sufficiently long.

As a result of difficulties encountered in handling plasma sprayed tape, a second tape was wound and the 2024 aluminum powder was brushed on from a dilute slurry of the following composition:

2024 powder - 60g
polystyrene - 5g
toluene - 195 ml

The polystyrene binder provided good adhesion of the fibers to the foil substrate, and as a result, the tape could be handled and cut with no difficulty.

Table II

NASA-Hough Monofilament/2024 Aluminum Composites
Plasma-Sprayed Tape
Tensile Data
$[(\pm 45)/(0)_4/(\mp 45)]_T$

		Fabrication Conditions				UTS	
No.	Fiber Vol (%)	Temp (°C)	Pressure MN/m^2	(ksi)	Time min.	GN/m^2	(ksi)
2132-1	51	450	69	10	30	0.29	42
-2	51					0.34	49
2150-1	50	450	103	15	30	0.20	29
-2	47					0.19	27
2151-1	49	450	34	5	60	0.38	55
-2	49					0.33	48
2155-1	52	450	34	5	30	0.31	45
-2	46					0.30	43

Five angleply composites were prepared from this tape which was reinforced with 0.0081 cm (3.2 mil) NASA-Hough monofilament from spool No. 4. The fabrication conditions and the tensile strength data are presented in Table III. Two tensile strengths are given for each composite: those actually measured, and the measured values normalized to 50 vol % fiber to permit a better comparison with previous data listed in Table II on composites of nominally 50 vol %.

Composite 2158 was a repeat of 2151 made from plasma sprayed tape to determine the reproducibility of the process with the different tapes. The data were in fairly good agreement, with the normalized strengths of the slurry coated tape being somewhat higher than those of the plasma sprayed tape. The highest measured strength of 0.42 GN/m^2 (61 ksi) was obtained on a composite fabricated at 450°C for 2 hrs under a nominal pressure of 21 MN/m^2 (3 ksi). However, the other specimen cut from the composite had a significantly lower strength and was thicker, indicating a nonuniform pressure distribution during fabrication. This means that the high strength specimen was probably under a pressure somewhat greater than 21 MN/m^2 during fabrication.

Three composites were hot pressed at 490°C for 60 min under various pressures. The best strength was measured on the composite pressed at the highest pressure (34 MN/m^2), but the differences among all the strengths were not great.

The generally low fiber volume fractions of the composites made from the slurry-coated tape illustrate the problem of uniformity control in brushing on a slurry of aluminum powder. As a result, a series of trial and error experiments was conducted in which the dilute slurry was sprayed using an aerosol can. The intent of the study was to deposit the same amount of powder on 2024 foil as is deposited in the plasma spray process since composites made from the latter tapes contain the desired 50 vol % fibers. After several trials it was found possible to produce a very uniform deposit of the proper amount. Precursor tape made by this technique was evaluated under Task III - Size Scale-Up and Process Optimization.

Table III

NASA-Hough Monofilament/2024 Aluminum Composites
Slurry-Coated Tape

Tensile Data
$[(\pm45)/(0)_4/(\mp45)]_T$

	Fiber	Fabrication Conditions				Measured		Normalized*	
	Vol	Temp	Pressure		Time	UTS		UTS	
No.	%	°C	MN/m^2	(ksi)	min	GN/m^2	(ksi)	GN/m^2	(ksi)
2158-1	44	450	34	5	60	0.36	52	0.41	59
-2	40					0.32	46	0.39	57
2159-1	38	450	21	3	120	0.29	42	0.38	55
-2	44					0.42	61	0.48	69
2160-1	41	490	21	3	60	0.28	40	0.34	49
-2	44					0.32	47	0.37	53
2161-1	42	490	14	2	60	0.34	49	0.40	58
-2	39					0.30	43	0.38	55
2169-1	40	490	34	5	60	0.29	42	0.36	52
-2	43					0.37	53	0.43	62

*Normalized to 50 v/o fiber

V. TASK III - SIZE SCALE-UP AND PROCESS OPTIMIZATION

The objectives of this task were to optimize the angleply composite fabrication parameters and to scale up the fabrication process to demonstrate the feasibility of making larger panels. The most promising processing parameters from Task II were to be used as the starting point, and these were to be modified in a minor manner in order to improve the composite tensile strength. Following the optimization a larger panel was to be made and tested to determine the effect of scale-up on composite tensile properties.

5.1 Process Optimization

Following development of the aerosol spray technique as described previously, a precursor tape was wound and sprayed. Reinforcement for the tape was 0.0081 cm (3.2 mil) NASA-Hough monofilament from spool No. 4. Composite fabrication conditions were selected based on previous results with plasma-sprayed and brushed slurry tapes.

The process optimization fabrication conditions and the tensile strengths of specimens machined from the laminates are presented in Table IV. The strength data indicate that the best fabrication conditions were 450°C, 34 MN/m^2 (5 ksi), 2 hrs. The average strength of the two specimens tested from the laminate was 0.39 GN/m^2 (56.5 ksi) which was significantly higher than that of any other laminate fabricated from the aerosol-sprayed tape. In addition, it was higher than all other strengths measured on laminates made from plasma-sprayed and slurry-coated tapes. Based on these superior strength results this set of conditions was selected for the fabrication of a scaled-up panel.

5.2 Scale-Up

In order to demonstrate the feasibility of producing larger panels than the 7.6 cm x 2.54 cm (3 in. x 1 in.) size used in the development and optimization of fabrication techniques, a panel size of 15.3 cm x 15.3 cm (6 in. x 6 in.) was selected for fabrication. Ply configuration for the laminate was to be the same as that used previously in the program, $[(\pm 45)/(0)_4/(\mp 45)]_T$.

5.2.1 Experimental Procedure

A precursor tape, 15.3 cm wide x 1.53 m long (6 in. x 5 ft) was prepared using the aerosol spray procedure described previously. Spacing of the 0.0081 cm NASA-Hough monofilament was 88 per cm (224 per in.). Three coats of powder were applied by the aerosol method.

Table IV

NASA-Hough Monofilament/2024 Aluminum Composites
Aerosol-Sprayed Tape
Tensile Data
$[(\pm 45)/(0)_4/(\mp 45)]_T$

No.	Fiber Vol. (%)	Fabrication Conditions				UTS	
		Temp °C	Pressure MN/m²	Pressure (ksi)	Time hrs	GN/m²	(ksi)
2177-1	41	450	21	3	2	0.41	60
-2	38					0.31	45
2179-1	42	450	34	5	2	0.36	52
-2	42					0.42	61
2180-1	42	490	34	5	2	>0.28[1]	>41[1]
-2	40					0.38	55
2181-1	44	490	21	3	2	>0.24[1]	>35[1]
-2	39					0.32	47
2182-1	41	490	21	3	3	0.37	53
-2	39					>0.30[1]	>44[1]

[1] Doublers unbonded during test

The procedure for fabricating the composite was as follows:

a. Cut plies in desired orientation and stack with foil side down.

b. Place additional foil layer on top of layup to produce balanced construction.

c. Place 0.00254 cm (0.001 in.) stainless steel foil on top and bottom of layup and tack weld around edges to provide lateral constraint to laminate during hot pressing.

d. Place enclosed layup in a stainless steel vacuum bag having an argon inlet port; cut corner of bag opposite inlet to provide escape for volatilizing polystyrene.

e. Place bag in hot press; apply positive pressure of argon of 41.3 KN/m^2 (6 psi); apply contact pressure.

f. When platen temperature reaches 450°C, hold for 1/2 hr to allow polystyrene to completely volatilize, then apply full pressure of 34 MN/m^2 (5 ksi) for a period of two hours.

Tensile specimens were cut from the laminate in both the longitudinal and transverse directions for testing at room temperature and 427°C. Specimen dimensions and testing procedures were the same as those described previously. For those tests conducted at 427°C, specimens were given a 15 minute soak at temperature prior to the initiation of the test in order to insure temperature equilibrium.

5.2.2 Results and Discussion

The large laminate was successfully hot pressed and appeared to be well-consolidated. The results of the room temperature and elevated temperature tensile tests on specimens cut from the laminate are presented in Table V. Specimens with an "L" in the number were tested in the longitudinal direction, while those with a "T" in the number were tested in the transverse direction. Considering first the room temperature results, the ultimate strengths of the composites tested in the longitudinal direction compared very well with those measured previously in the program on specimens cut from small laminates. The strength of composite 2215-L2 was the highest measured up to that time.

Table V

NASA-Hough Monofilament/2024 Aluminum Composites
Aerosol-Sprayed Tape
Tensile Data
$[(\pm 45)/(0)_4/(\mp 45)]_T$

No.	Fiber Vol (%)	Test Temp (°C)	UTS GN/m^2	UTS ksi	Modulus GN/m^2	Modulus msi	Failure Strain %
2215-L2		21	0.44	63.5	78.5	11.4	1.08
2215-L3		21	0.41	60.0	95.1	13.8	0.99
2215-T1		21	0.14	20.7	80.0	11.6	0.62
2215-T2		21	0.15	21.8	79.3	11.5	0.60
2215-L4		427	0.28	40.3	79.3	11.5	-
2215-L5		427	0.32	46.6	78.6	11.4	0.80
2215-T3		427	0.088	12.7	39.4	5.7	>0.92
2215-T4		427	0.094	13.6	28.3	4.1	>1.08

The transverse tensile strengths were also quite good and were very consistent indicating uniform composite quality. It was somewhat surprising that the average transverse tensile modulus was nearly as high as that for the composites tested in the longitudinal direction. There was a large difference in the moduli of the two longitudinal specimens, however, and there may have been a problem with the measurement for specimen 2215-L2, although none was evident. The modulus of specimen 2215-L3 was in the expected range.

The longitudinal tests conducted at 427°C demonstrated a very similar strength retention to that shown for unidirectional composites in Ref. 1. Under the previous contract, unidirectional composites were found to retain 76 percent of their room temperature strength when tested at 427°C. The data in Table V indicate that the angleply composites retained 71 percent of their room temperature strength which leads to the conclusion that the unidirectional core of the angleply composites controlled their tensile strength, as would be expected.

The angleply composites demonstrated a much better retention of transverse tensile strength at elevated temperature than did the unidirectional composites. The unidirectional materials in Ref. 1 retained only 20 percent of their room temperature strength at 427°C, while the angleply composites retained 57 percent in this study. This indicates that the 45° plies made a significant contribution to the transverse tensile strength behavior of the angleply composite.

In view of the good results obtained with the scaled-up panel, the fabrication process was not modified for the production of laminates for full characterization in Task IV.

VI. TASK IV - FABRICATION AND CHARACTERIZATION OF ANGLEPLY COMPOSITES

The objective of this task was to conduct a series of tests to characterize the mechanical behavior of angleply NASA-Hough carbon monofilament/2024 composites. Composite panels were produced using the optimized processing procedures developed during the previous tasks. These panels were machined into specimens which were tested to determine the properties of the material in tension, stress-rupture, fatigue, thermal cycling, and impact. The reinforcement utilized in the bulk of this study was the 3.2 mil filament, with very limited work done with the 5.6 mil filament.

The following sections describe the apparatus and procedures used in each test area, and present the results and discuss their significance.

6.1 Tension Testing

6.1.1 Experimental Procedure

Tension testing was carried out at room temperature (23°C), 260°C, and 427°C in both the longitudinal and transverse directions. The test specimen in all cases was a straight-sided bar, 21 cm x 1.27 cm x 0.089 cm (3 in. x 1/2 in. x .035 in.). Aluminum doublers were bonded on the room temperature specimens, while copper doublers were inserted between the specimen and the grips for elevated temperature tests. Gage length between doublers was 2.54 cm (1 in.), and cross-head speed was .0254 cm/min (.01 in./min). Strain was measured by strain gages which were adhesively bonded to both sides of the specimen to eliminate any bending effects.

6.1.2 Results and Discussion

The results of the tensile tests are presented in Table VI. The room temperature strengths were significantly better than those measured during Task III on panel 2215, apparently due to a higher filament volume fraction. The Task IV composites averaged 52 v/o while composite 2215 made in Task III, averaged 46 v/o. The longitudinal strengths of composites 2264 and 2265 were particularly good, averaging 0.545 GN/m^2 (79.1 ksi) versus an average of 0.425 GN/m^2 (61.7 ksi) for composite 2215.

The room temperature transverse tensile strength of the composites was also quite good, in view of the very low strengths which were measured in the previous contract for unidirectional composites tested in the transverse direction, (57.2 MN/m^2, 8.3 ksi). Figure 6 is a scanning electron micrograph of the fracture surface of a transverse tensile specimen. The top photograph indicates that a reasonably good bond existed between the filaments and the aluminum matrix in

Table VI

Tensile Data
3.2 mil NASA-Hough Monofilament/2024 Aluminum
$[(\underline{+}45)/(0)_4/(\mp 45)]_T$

No.	Test Direction	Test Temp. °C	UTS GN/m^2	UTS (ksi)	Modulus GN/m^2	Modulus (msi)	Failure Strain %
2265-L1	Longitudinal	23	0.58	83.5	106	15.4	0.93
2264-L11	↓	↓	0.54	76.3	101	14.6	0.90
2265-L12	↓	↓	0.56	81.2	98.0	14.2	0.97
2265-L14	↓	↓	0.52	75.4	96.5	14.0	0.92
2266-T1	Transverse	↓	0.15	22.2	73.8	10.7	0.95
2266-T2	↓	↓	0.18	26.6	91.4	13.4	0.84
2215-L6	Longitudinal	260	0.40	57.8	93.0	13.5	–
2215-L13	↓	↓	0.44	63.8	94.2	13.8	–
2265-L3	↓	↓	0.46	67.0	88.3	12.8	0.82
2265-L6	↓	↓	0.45	65.7	84.1	12.2	0.82
2266-T3	Transverse	↓	0.17	24.6	68.3	9.9	0.81
2266-T4	↓	↓	0.13	18.4	77.9	11.3	0.64
2265-L2	Longitudinal	427	0.33	48.5	61.3	8.9	>0.60
2265-L5	↓	↓	0.34	49.0	66.9	9.7	0.64
2265-L7	↓	↓	0.29	42.7	72.4	10.4	>0.42
2265-L11	↓	↓	0.30	43.5	103	15.0	>0.46
2266-T5	Transverse	↓	0.10	15.3	60.7	8.8	>1.08
2266-T6	↓	↓	0.11	16.1	52.4	7.6	>1.02

that many of the filaments were at least partially covered with aluminum. Transverse tensile fracture surfaces examined in the previous contract consisted almost entirely of bare filament.

The reason for the difference may be related to evidence in the lower photograph in Fig. 6. The filament in the center of the photograph can be seen to have mottled areas which appear to be shallow pits over a portion of its surface. A closer look at another filament having similar features is provided in Fig. 7. The photograph shows that traces of aluminum remained bonded to the filament in the darker areas, while the lighter areas were bare. It is possible that the dark areas, which appear to be slight depressions in the filament, were regions of reaction between the filament and the matrix during fabrication, thus creating a good interfacial bond. The fabrication conditions utilized in this contract involved a two hour hold at 450°C, while under the previous contract there was a 30 minute hold at 450°C. The longer time during hot pressing may have been sufficient to allow some reaction to occur. It is also possible that the surface of the current filament was chemically different and therefore more reactive than the filament used in the previous contract. Regardless of the cause, a small amount of reaction, such as appeared to have occurred, is believed to be desirable since the longitudinal strength properties were not degraded and the transverse strength properties apparently were improved.

The elevated temperature results in both the longitudinal and transverse directions were generally in the expected range. The longitudinal tests at 260°C and 427°C demonstrated room temperature strength retentions of 80 and 58 percent respectively. The percent retention at 427°C was lower than observed in Task III, but the absolute values were actually somewhat higher. Scanning electron micrographs of the fracture surface of a longitudinal specimen tested at 427°C (Fig. 8) indicate that even at elevated temperature the filament pullout length was not too great. This further verifies the improved bond strength between the filament and the matrix.

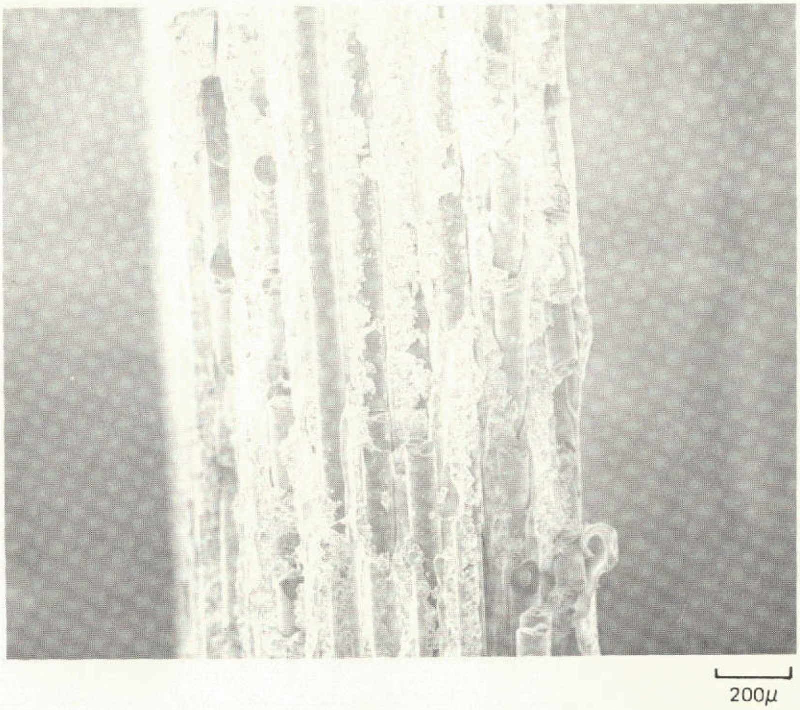
The transverse tests again demonstrated the effectiveness of the 45° plies in carrying loads. There was a 65 percent retention of room temperature strength, even at a test temperature of 427°C. One value at the 260°C test temperature was actually higher than the room temperature strengths.

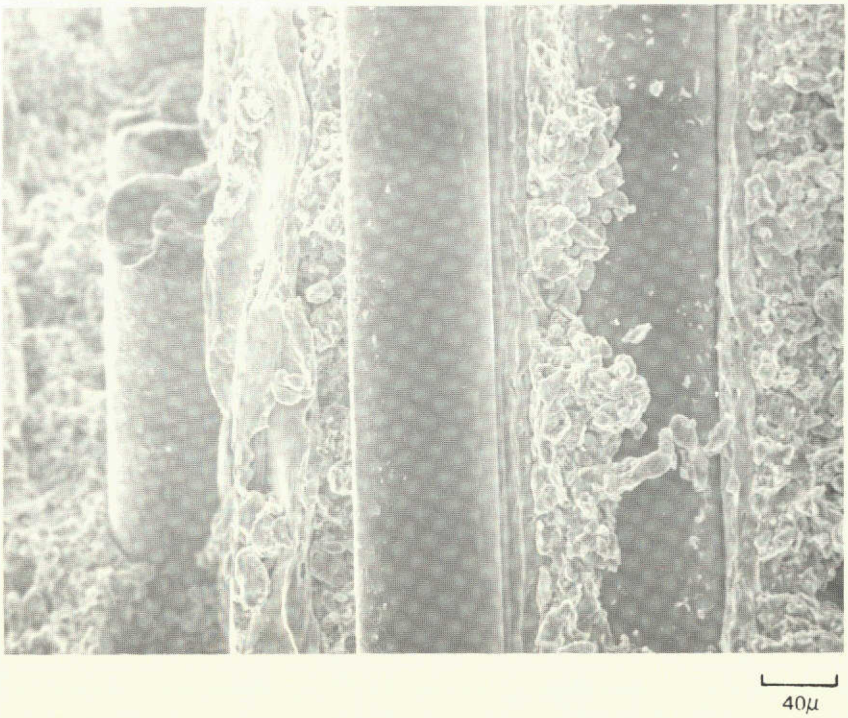
Taken as a whole the tensile tests of the composites reinforced with the 3.2 mil filament were very encouraging. The specific gravity of a composite specimen was measured at 2.277 g/cc (.081 lbs/in^3). Using this information, specific strengths were calculated and compared with literature values for BORSIC®-aluminum composites (Ref. 3). Unfortunately, the only data available in Ref. 3

23°C TRANSVERSE TENSILE FRACTURE SURFACE

NASA–HOUGH MONOFILAMENT / 2024 ALUMINUM

[($\pm$ 45) / $(0)_4$ /) ($\mp$ 45)]





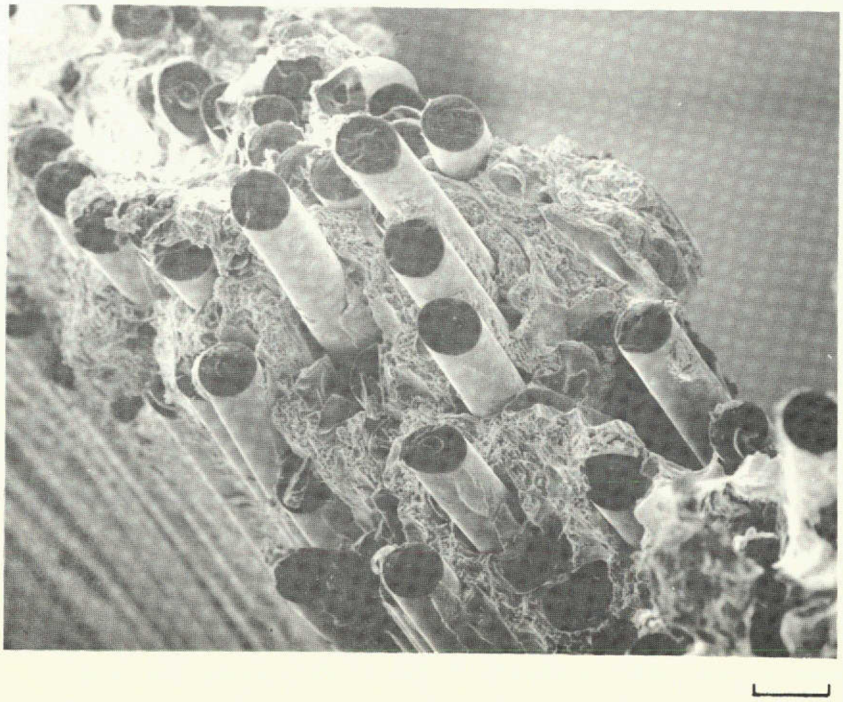
SURFACE OF NASA–HOUGH MONOFILAMENT

427°C LONGITUDINAL TENSILE FRACTURE SURFACE

NASA–HOUGH MONOFILAMENT / 2024 ALUMINUM

$[(\pm 45)/(0)_4/(\mp 45)]$

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR



for a similar construction had a greater percentage of 0° plies, $[(\underline{+}45)/(0)_6/(\underline{+}45)]_T$. However, a reasonable approximation of the strength of BORSIC composites of the same construction as used in this program can be made by assuming each 45° ply in the BORSIC composite contributed .207 GN/m^2 (30 ksi) and each 0° ply contributed 1.045 GN/m^2 (150 ksi). This works out to a strength of 0.703 GN/m^2 (102 ksi) for the BORSIC laminate above, which is the value given in Ref. 3. Using this logic, the strength of a $[(\underline{+}45)/(0)_4/(\underline{+}45)]_T$ construction of BORSIC-aluminum would be 0.62 GN/m^2 (90 ksi). The specific gravity of BORSIC-aluminum is approximately 2.7 g/cc (.097 lbs/in^3), and dividing the calculated strength by this value results in a specific strength of 2.36 x 10^6 cm (9.38 x 10^5 in.). Dividing the measured longitudinal strength of the NASA-Hough angleply composite by its specific gravity results in a specific strength of 2.48 x 10^6 cm (9.78 x 10^5 in.). Even using the literature value of 0.703 GN/m^2 (102 ksi) for the strength of the $[(\underline{+}45)/(0)_6/(\underline{+}45)]_T$ laminate results in a specific strength of only 2.62 x 10^6 cm (10.5 x 10^5 in.), just slightly higher than the value for the carbon-aluminum laminate with fewer 0° plies.

A limited number of tests was conducted on composites reinforced with 5.6 mil filament, and the results are given in Table VII. The room temperature longitudinal strengths were essentially the same as those of the optimized 3.2 mil filament composites. It should be noted that only a limited amount of 5.6 mil filament was available for study under this contract, and it is very likely that the procedures for making the precursor tape were not optimum, thus leading to less than ideal composite quality. This fact was reflected in the transverse tensile strength of composite 2221-1 which was quite low.

6.2 Stress-Rupture

6.2.1 Experimental Procedure

Longitudinal stress-rupture tests were carried out at 260°C and 427°C in constant load machines, the temperature being monitored with chromel-alumel thermocouples positioned adjacent to the specimen. Friction type grips were used with copper doublers to protect the specimen surface. The machines shut off automatically upon fracture of the sample and the time to rupture was recorded to the nearest 0.1 hr. The intent of the tests was to measure the stress to rupture at 100 hrs for each temperature.

Creep tests were also conducted at 260°C and 427°C. The test machine was similar to those used for stress rupture except that elongation was continuously recorded during the test by means of an extensometer activated LVDT. The extensometer was attached to the grips holding the specimen.

Table VII

Tensile Data
5.6 mil NASA-Hough Monofilament/2024 Aluminum
$[(\pm 45)/(0)_4/(\mp 45)]_T$

No.	Test Direction	Test Temp °C	UTS GN/m^2	UTS (ksi)	Modulus GN/m^2	Modulus (msi)	Failure Strain %
2220-1	Longitudinal	23	0.55	79.0	95.1	13.8	0.68
2220-2	↓	23	0.49	71.6	98.6	14.3	0.70
2220-5	↓	427	0.21	30.2	88.2	12.8	0.30
2221-1	Transverse	23	0.02	2.9	53.8	7.8	0.09

6.2.2 Results and Discussion

The results of the stress-rupture tests at 260°C and 427°C are summarized in Figs. 9 and 10, respectively. The tests conducted at 260°C indicated a very low susceptibility to stress-rupture effects. Specimens tested at stress levels within the scatter of the static strength survived for over 100 hrs without failure. Similar conclusions were reached in Ref. 1 regarding the stress-rupture behavior of unidirectional composites tested at 260°C. As a result of these tests, the stress to cause rupture in 100 hrs of the $[(\pm 45)/(0)_4/(\mp 45)]_T$ construction at 260°C is estimated to be 0.28-0.405 GN/m^2 (55-60 ksi).

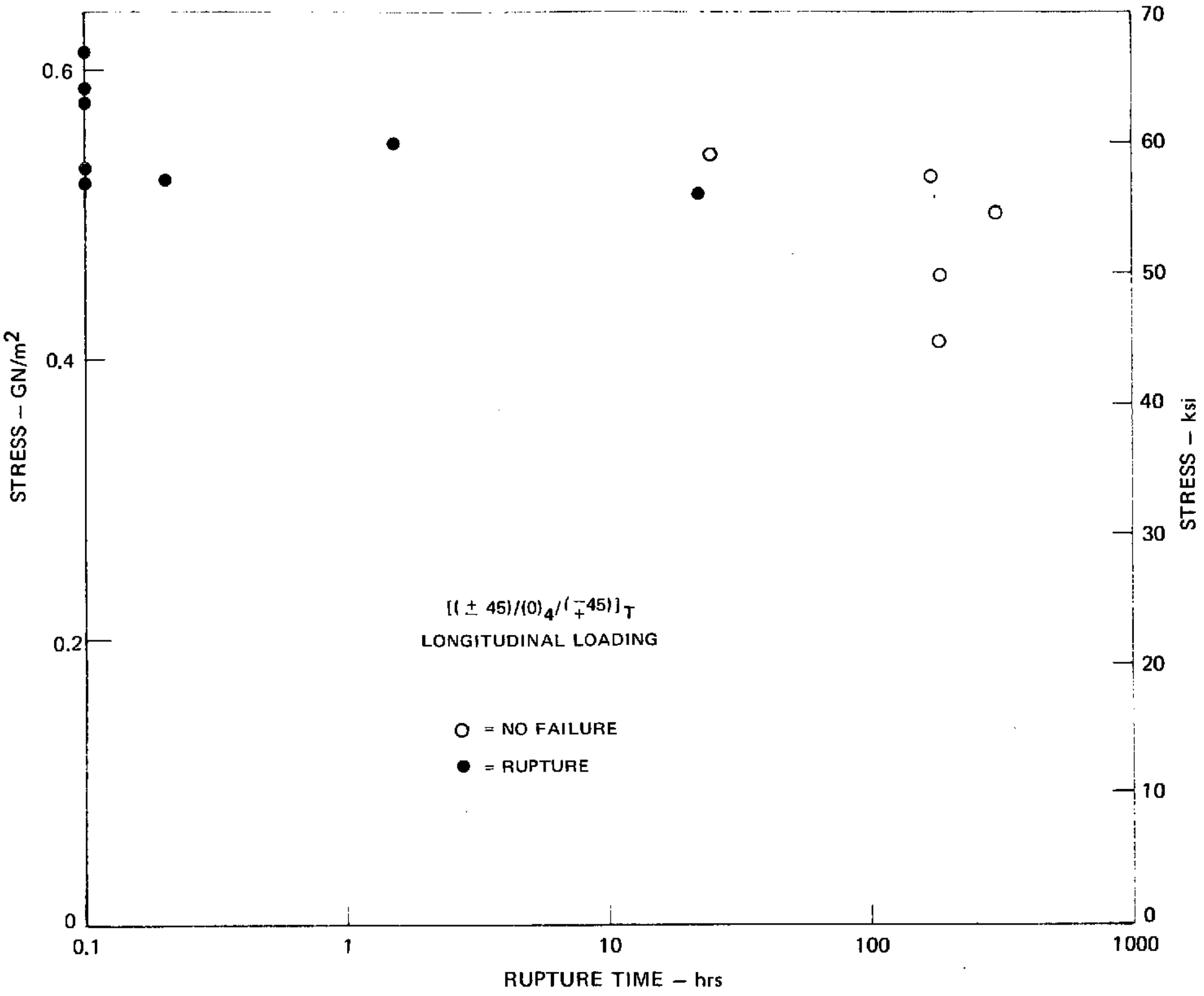
The tests at 427°C showed a greater effect, again in a manner similar to the unidirectional results reported in Ref. 1. The stress for rupture in 100 hrs at 427°C is estimated to be 0.242-0.262 GN/m^2 (35-38 ksi). Figure 11 shows a fracture surface of the specimen which failed after 26 hrs at 0.276 GN/m^2 (40 ksi). There appeared to be more filament pullout than was evident in the static tests conducted at the same temperature.

Creep curves at 260°C and 427°C are presented in Figs. 12 and 13, respectively. Stress levels were selected to be in the range of the 100 hr stress-rupture life level. The 260°C test was interrupted after 114 hrs without having failed the specimen. The steady state creep rate was extremely low and clearly demonstrated that under a stress of .345 GN/m^2 (50 ksi) axial creep is not an important consideration for the time period studied.

The test at 427°C under a stress of .255 GN/m^2 (37 ksi) indicated that the material has definite limitations at that temperature. Truly steady state creep was not observed, and the specimen failed after 1.5 hrs. The approximate creep rate was an order of magnitude greater than that reported in Ref. 1 for a unidirectional specimen tested at 427°C under a stress of .428 GN/m^2 (62 ksi). This indicates that the 45° plies had a drastic effect on the creep behavior of the angleply specimen. This was not unexpected since the matrix becomes highly stressed in a ±45° configuration and the creep behavior of aluminum alloys at 427°C is not good.

6.3 Mechanical Fatigue

Fully reversed cantilever bending tests were performed on angleply composites with the 0° plies in the long direction of the specimen. Bending was selected as the loading mode since it simulates the conditions experienced by gas turbine engine blades in service. Unidirectional carbon monofilament/aluminum composites were shown to be subject to damage due to bending fatigue under the previous contract.



STRESS–RUPTURE AT 260°C
NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

FIG. 9

N06–55–2

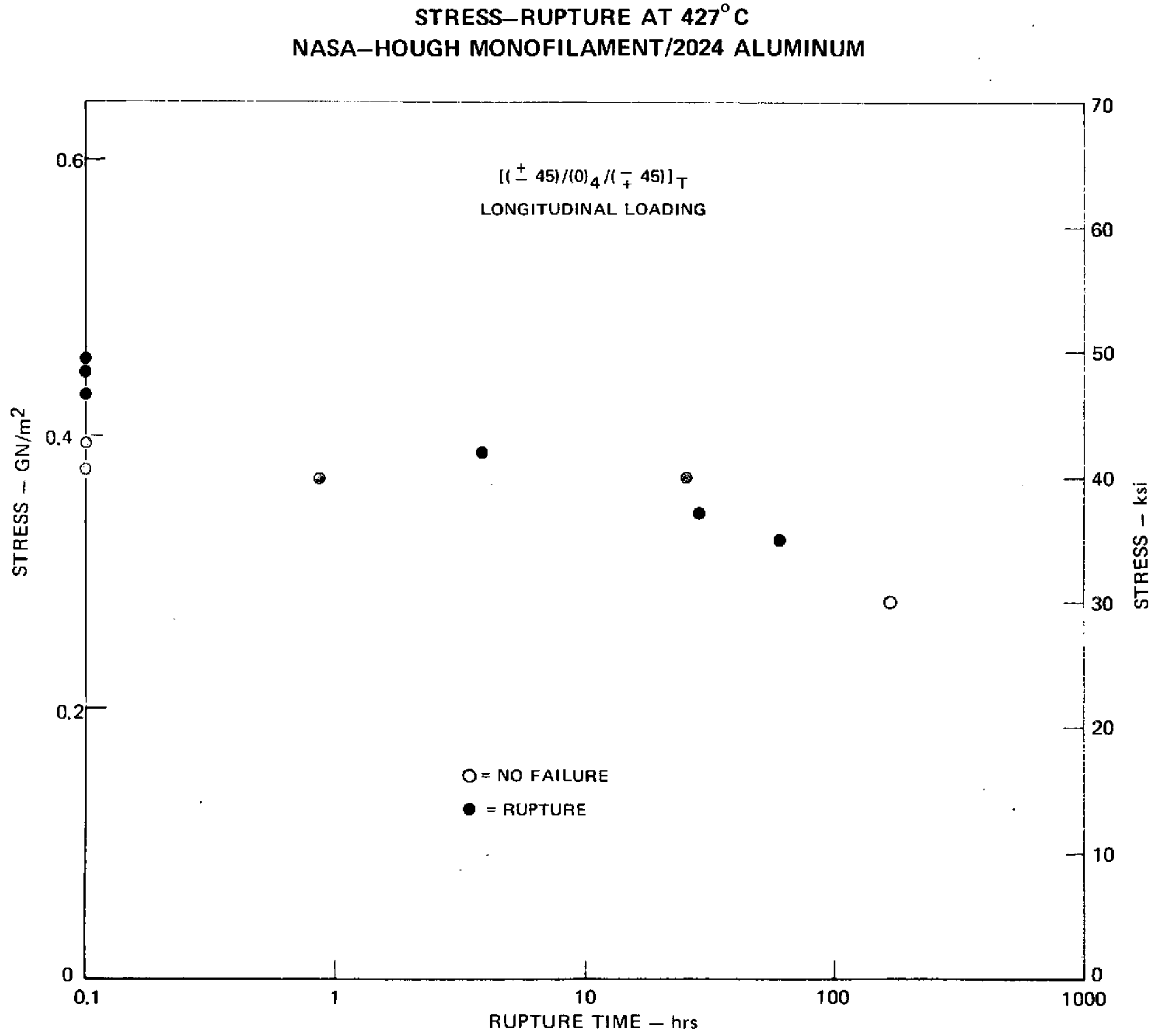

STRESS–RUPTURE AT 427°C
NASA–HOUGH MONOFILAMENT/2024 ALUMINUM
$[(\pm 45)/(0)_4/(\mp 45)]_T$
LONGITUDINAL LOADING
○ = NO FAILURE
● = RUPTURE
STRESS – GN/m²
0
0.2
0.4
0.6
STRESS – ksi
0
10
20
30
40
50
60
70
0.1
1
10
100
1000
RUPTURE TIME – hrs

FIG. 10

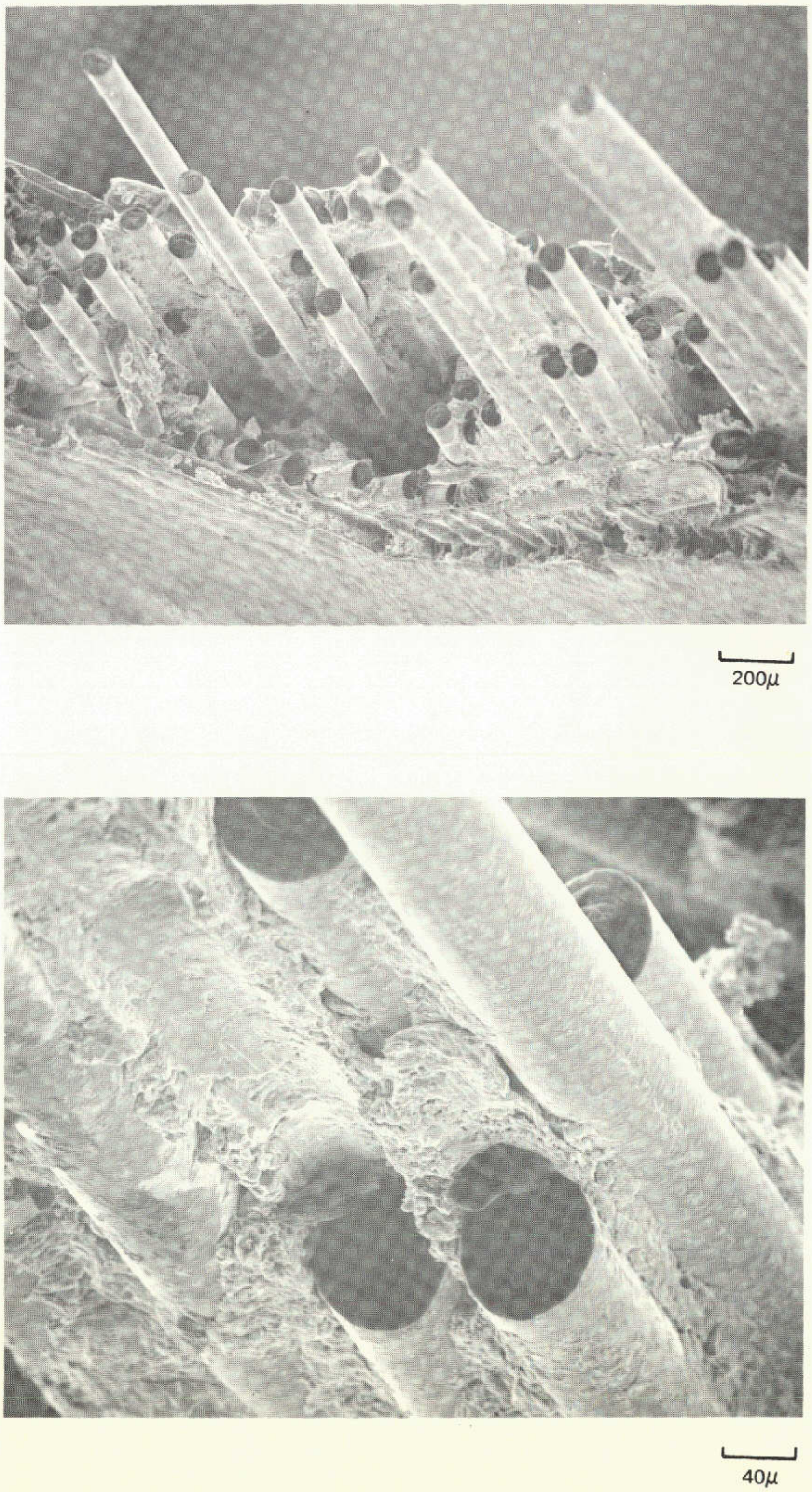
FIG. 11

STRESS–RUPTURE FRACTURE SURFACE

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

$[(\pm 45)/(0)_4/(\mp 45)]_T$

427°C, 0.276 GN/m^2 (40 ksi), 26.1 hrs.

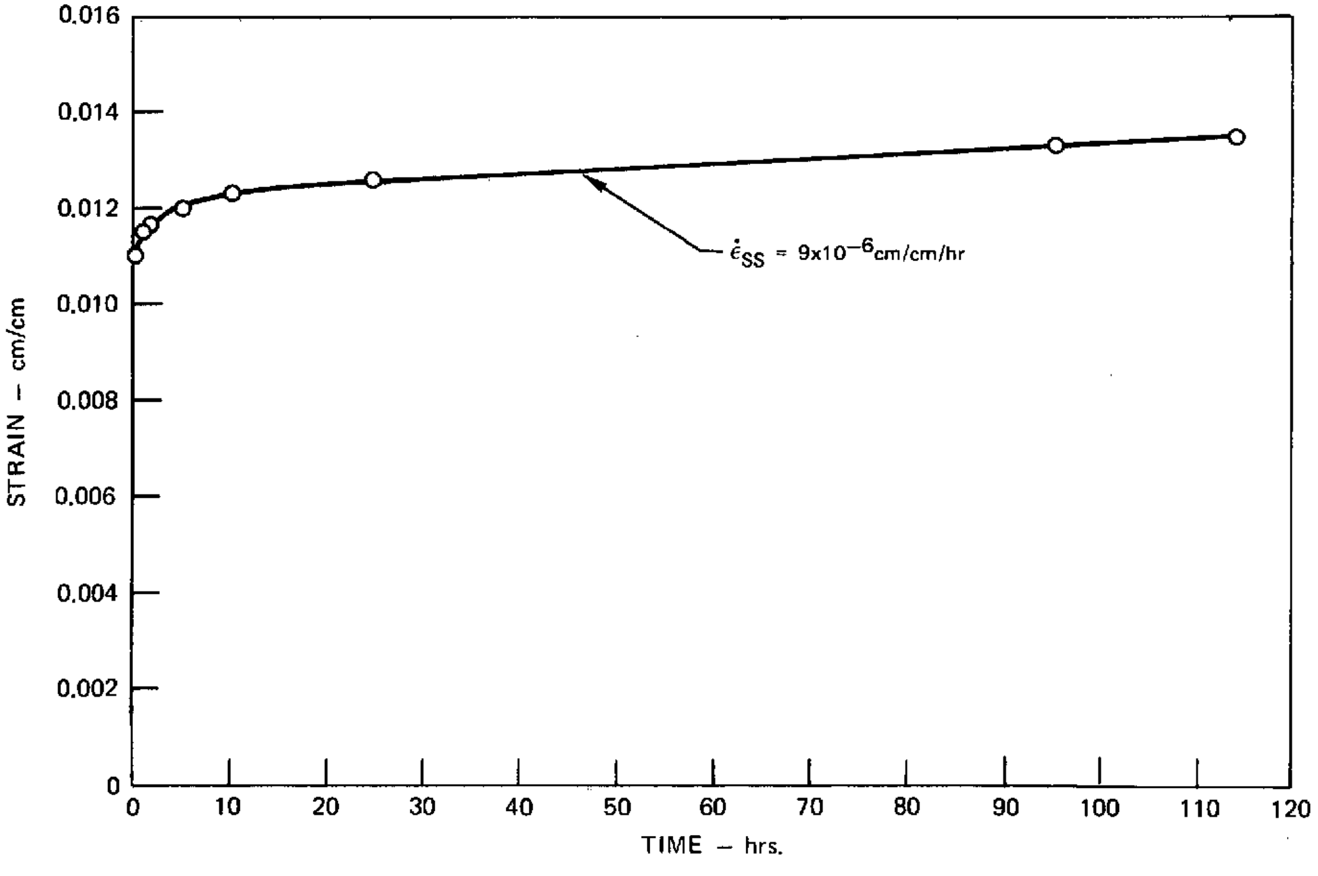


CREEP BEHAVIOR

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

260°C

0.345 GN/m^2 (50 ksi)



CREEP BEHAVIOR

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

$[(\pm 45)/(0)_4/(\mp 45)]_T$

427°C

0.262 GN/m^2 (38 ksi)

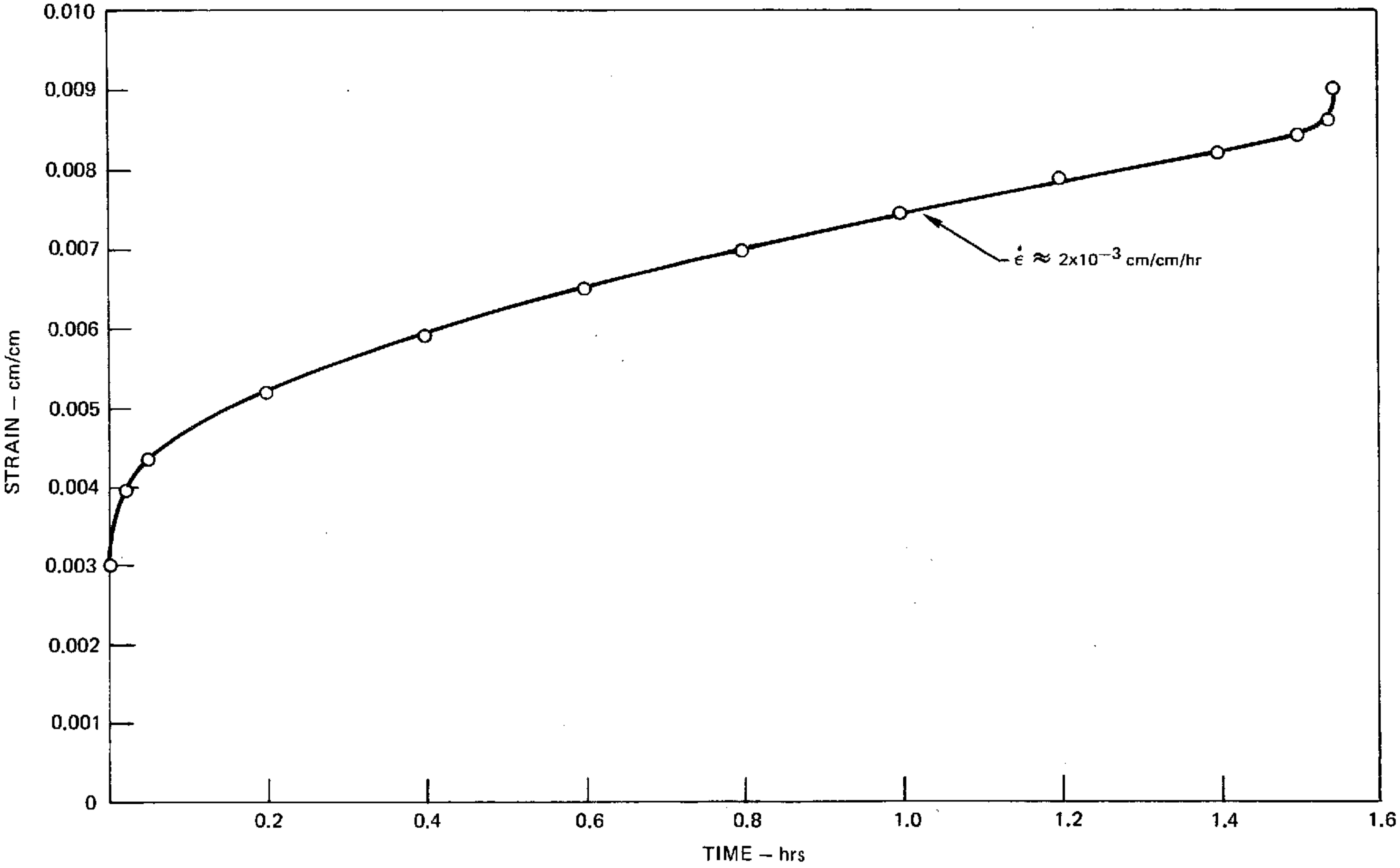


FIG.13

6.3.1 Experimental Procedure

The test specimen was nominally 7.6 cm x 1.27 cm x .089 cm (3 in. x .5 in. x .035 in.) with a cantilever length of 4.27 cm (1.75 in.). Testing speed was varied between 500 cpm and 2500 cpm in order to measure both low cycle and high cycle (1×10^6) behavior. In order to minimize stress concentrations, thin rubber pads were inserted between the specimen and the holding fixture at the moving end. The fixed end was rigidly held in a steel clamp. The apparatus produced constant deflection loading, and the stress was varied from specimen to specimen by changing the deflection. Since a portion of the deflection imparted to the specimen was taken up by the rubber pads at the loading point, the actual strain in a specimen was determined with a strain gage which was bonded as near to the fixed end as possible. A calibration of specimen strain vs imposed deflection was made and the stress in other specimens was calculated using this calibration. It was found that the rubber took up approximately 12 percent of the imposed deflection.

The method used to determine damage as a result of fatigue loading was the same as that described in Ref. 1. It was found that the bending modulus of unidirectional specimens was gradually reduced during the fatigue process. Since the stiffness of gas turbine engine blades is a critical design parameter, a loss in stiffness could be used as a failure criterion. The stiffness reduction which might constitute failure in service would depend on the specific application. As a result, the objective of this study was to derive a family of curves of modulus reduction as a function of stress level and number of cycles. To do this the bending stiffness of each specimen was measured before the fatigue test and at various intervals during the test by the dead weight loading technique described in Ref. 1. Intervals were selected to provide information after testing times ranging from 100 to 1×10^6 cycles, depending on the stress level.

6.3.2 Results and Discussion

The specimens and test conditions for the bending fatigue study are presented in Table VIII. Each test was interrupted several times prior to completing the total number of cycles indicated in the table, a static test was performed to measure the bending modulus, and the specimen was then reinserted in the bending fatigue test. Figure 14 shows typical results of such modulus measurements for specimen 2264-L9 tested at ± 72.3 MN/m^2 (10.5 ksi) and specimen 2264-L6 tested at ± 123 MN/m^2 (17.8 ksi). As the curves show there was generally not much scatter in the measurements, and the modulus decrease of the specimens did not exhibit any abrupt changes. All the specimens tested behaved in a manner similar to that shown in Fig. 14.

Table VIII

Bending Fatigue Test Conditions
NASA-Hough Monofilament/2024 Aluminum
$[(\pm 45)/(0)_4/(\mp 45)]_T$

Specimen No.	Alternating Deflection		Alternating Bending Stress		Total No. Cycles
	cm	(in.)	GN/m^2	(ksi)	
2264-L9	.23	.09	.072	10.5	1×10^6
2264-L14	.27	.11	.083	12.0	1×10^6
2264-L13	.31	.13	.100	14.5	1×10^6
2264-L6	.41	.16	.123	17.8	1×10^6
2264-L3	.43	.17	.151	21.9	5×10^3
2264-L1	.56	.22	.166	24.0	1×10^6
2264-L10	.56	.22	.167	24.2	1×10^5
2264-L2	.71	.28	.214	31.0	5×10^3

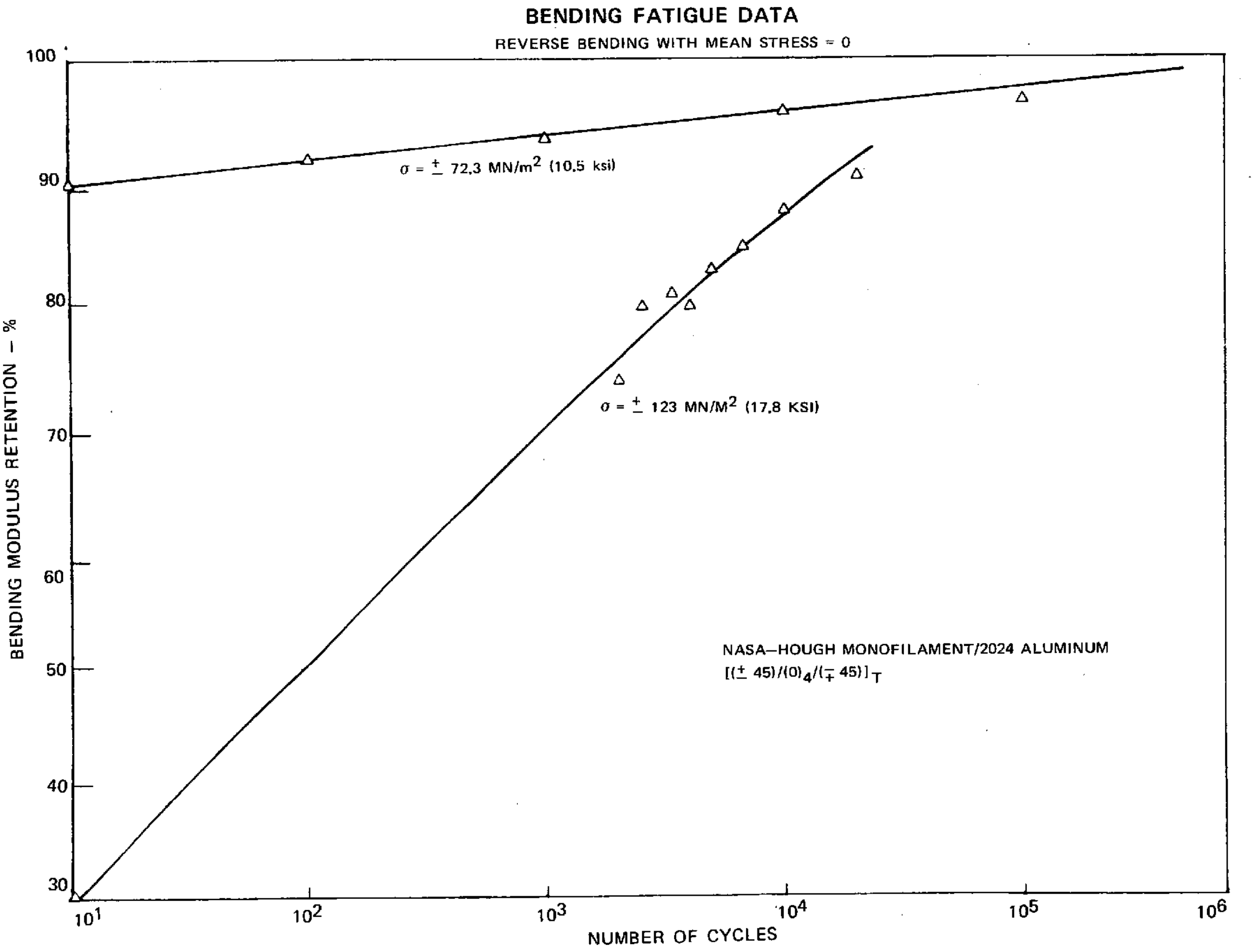


FIG.14

N06–55–4

The type of damage which was incurred is shown in Fig. 15, which is a photomacrograph of the edge of specimen 2264-L14 which had been tested for 1 x 10^6 cycles at a stress of ±82.7 MN/m^2 (12 ksi). The mode of failure was primarily delamination of both the 45° plies and the 0° plies. In addition, there was some fracture of the 45° plies, especially near the clamp edge where the bending stress was maximum. In no instance was any fracture of the 0° plies observed and none of the specimens fractured in the sense of breaking in two pieces. Samples which were tested at higher stresses exhibited more extensive delamination than that shown in Fig. 15.

In order to obtain the desired curves of modulus reduction as a function of stress level and number of cycles, the data for all specimens was plotted as in Fig. 14. The stress and number of cycles for retention of 60, 70, 80, and 90 percent of the original modulus were then determined and plotted in Fig. 16. Using curves such as these it would be possible to design a part to operate for a given lifetime at a stress level which would produce a permissible reduction in modulus. The data indicate an endurance limit of approximately 69 MN/m^2 (10 ksi) to which the material could be cycled for extended periods without further reduction in modulus.

Since the failure mode was primarily by delamination it is possible that the bending fatigue behavior of the material could be improved through further optimization of the fabrication process to increase the fiber-matrix bond. However, the static tensile data discussed previously indicated that higher pressure would not be satisfactory due to fiber breakage and higher temperature also had an adverse effect on strength. Longer time under pressure did not have a drastic effect on composite strength, and that would be one approach to explore. Another approach would be to investigate the effects of variation in ply configuration. The 0° core with a ± 45° shell construction utilized in this study has a very desirable combination of bending and torsional moduli which are primary design criteria. However, the large differences in thermal and elastic properties between the core and the shell create residual stresses and stress concentrations which very likely have an adverse effect on fatigue behavior. Thus, reducing the angle of the shell and/or increasing the angle of the core, or utilizing an interspersed combination of unidirectional and angleplies might improve the resistance of the material to fatigue.

6.4 Thermal Fatigue

6.4.1 Experimental Procedure

Composite thermal fatigue tests were conducted over two temperature ranges, 23°C to 260°C and 23°C to 427°C, for 500 and 1000 cycles. Specimen dimensions were the same as those previously described for tensile specimens.

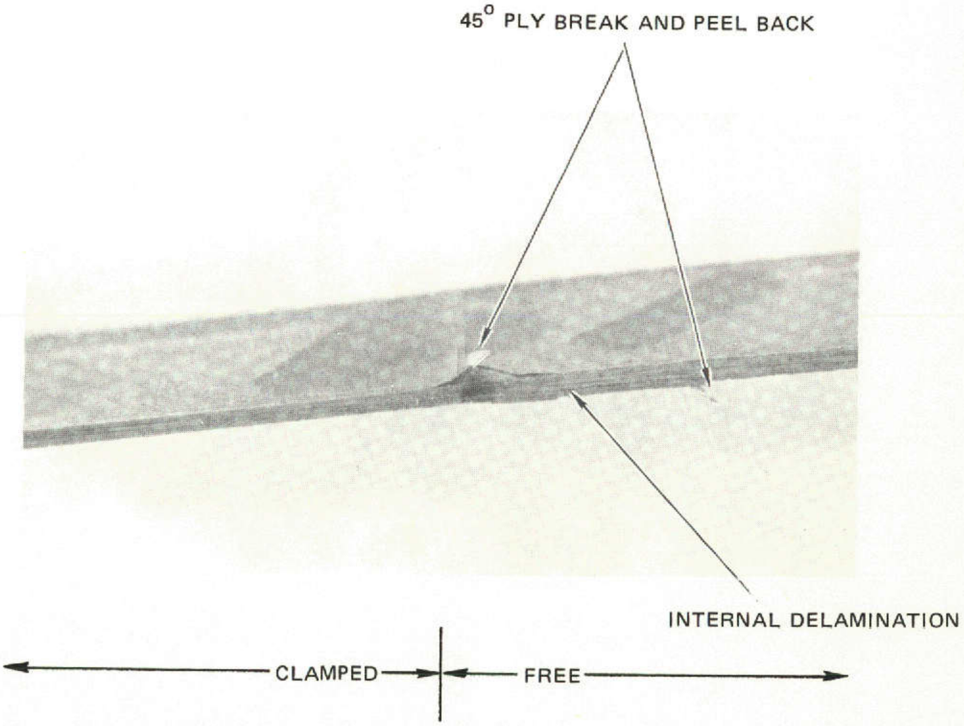
FIG. 15

BENDING FATIGUE DAMAGE

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

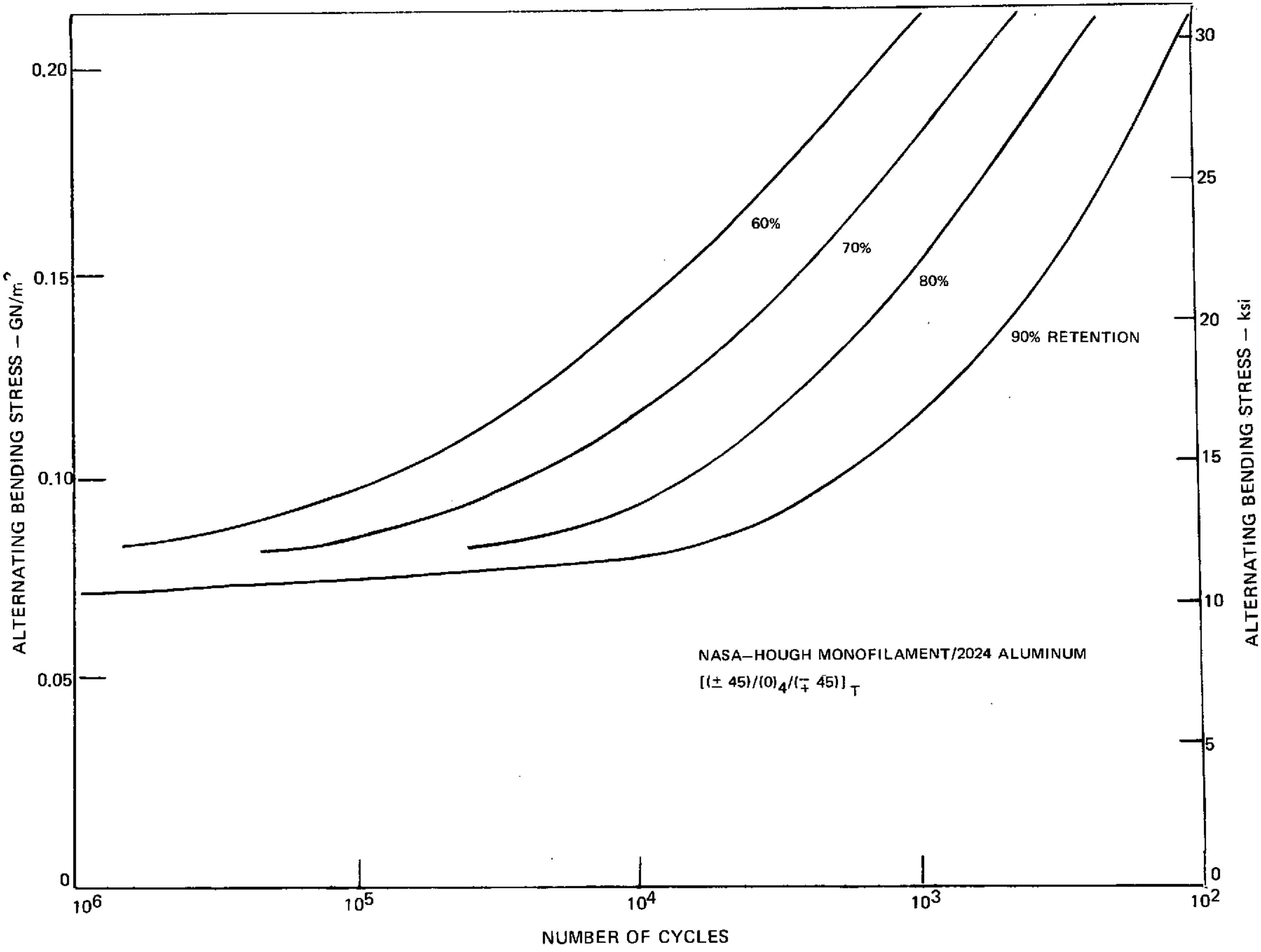
$[(\pm 45)/(0)_4/(\mp 45)]_T$

1×10^6 CYCLES @ $\sigma = \pm 82.7$ MN/m^2 (12 ksi)



BENDING MODULUS RETENTION AFTER FATIGUE

REVERSE BENDING WITH MEAN STRESS = 0



NASA–HOUGH MONOFILAMENT/2024 ALUMINUM
$[(\pm 45)/(0)_4/(\mp 45)]_T$

FIG. 16

The thermal cycling apparatus consisted of a vertical tube furnace and a motor driven screw which was used to raise the specimens into the furnace for heating, then lower the specimens out of the furnace for cooling. As the specimens emerged from the furnace, fans were activated to aid in cooling them to room temperature. The number of cycles was monitored with an automatic counter. Each heating and cooling cycle took five minutes.

Damage due to the thermal fatigue tests was determined by visual observation and by tension testing at room temperature after the desired number of cycles, then comparing the results with base line room temperature data previously reported. Test procedures for the thermally cycled specimens were identical to those used in measuring the base line properties. Specimens were tested in both the transverse and longitudinal directions.

6.4.2 Results and Discussion

The results of the thermal cycling tests on longitudinal specimens are presented graphically in Fig. 17 in terms of retention of longitudinal tensile strength. Specimens from panels 2215, 2264, and 2265 were tested. Since the base line strength of panel 2215 was less than that of the other two panels, 2264 and 2265, the data in Fig. 17 are shown by composite number to permit a meaningful measure of the effect of thermal cycling on composite strength. Base line strengths (0 cycles) were the averages of the tensile tests on each panel in the as-fabricated condition.

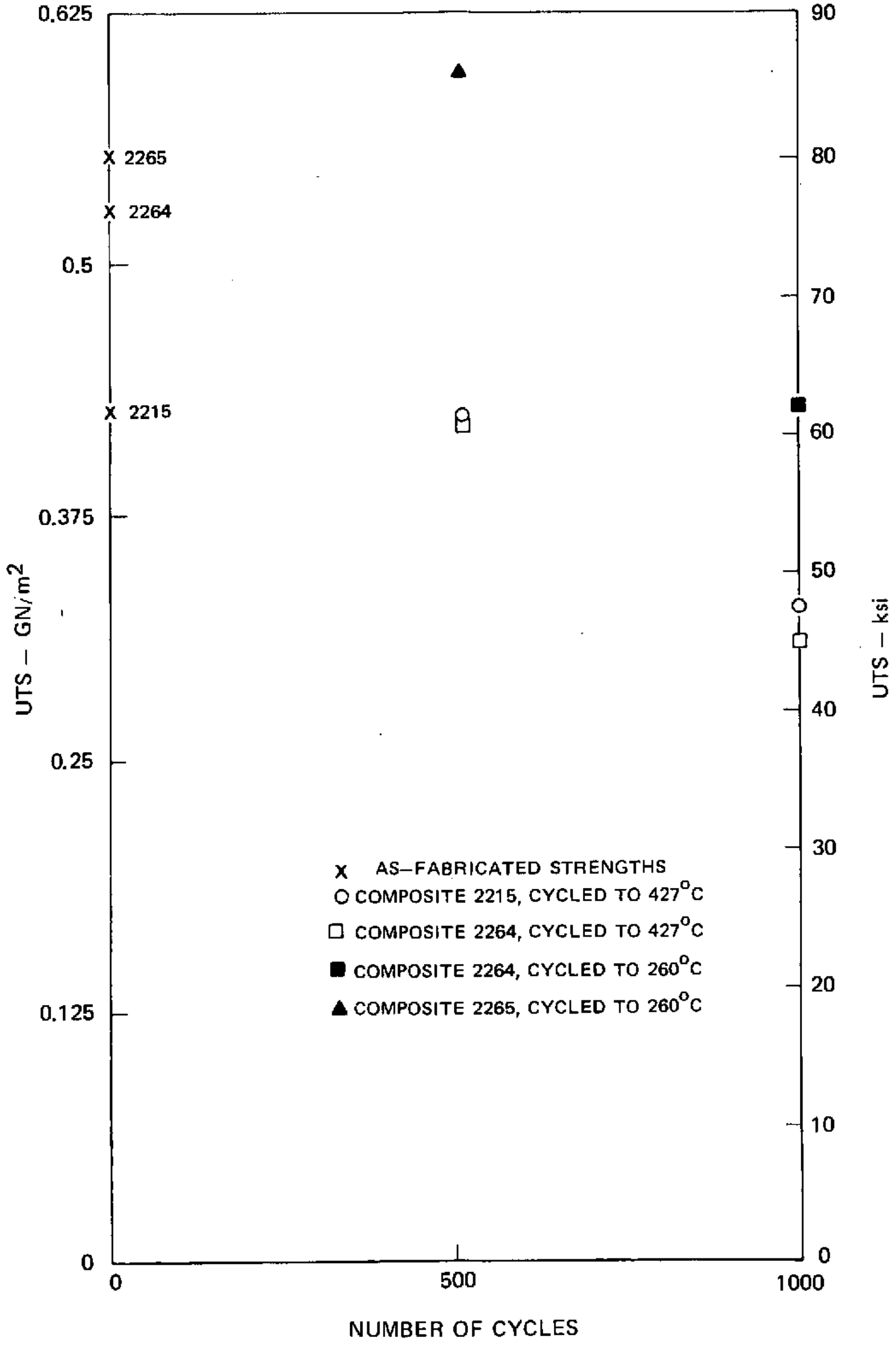
The test results indicated some reduction in longitudinal strength following 1000 cycles to 260°C. Based on an as-fabricated strength of 0.54 GN/m^2 (76 ksi) for panel 2264, the specimen suffered an 18 percent loss in strength after 1000 cycles. The specimen subjected to 500 cycles at that temperature had a strength higher than that of the as-fabricated material, indicating that no damage had occurred. In none of the tests was there any visual evidence of damage. Thus it appears that angleply composites of the material are capable of being cycled between room temperature and 260°C without significant reduction in tensile strength. This finding was confirmed in Ref. 1 in which it was demonstrated that similar thermal cycling had no effect on the longitudinal tensile strength of unidirectional NASA-Hough carbon-aluminum.

Tests conducted to a maximum temperature of 427°C did have an effect on the longitudinal specimens, especially after 1000 cycles. After 500 cycles, the specimen from panel 2215 had the same strength as the as-fabricated material, while the specimen from composite 2264 suffered a 21 percent loss in strength. After 1000 cycles, specimens from both panels exhibited a loss in strength.

EFFECT OF THERMAL CYCLING ON ROOM TEMPERATURE LONGITUDINAL TENSILE STRENGTH

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

$[(\pm 45)/(0)_4/(\pm 45)]_T$



In addition to the loss in strength, both specimens subjected to 1000 cycles to 427°C suffered some delamination as can be seen in Fig. 18. The degree of delamination was clearly greater for the specimen from panel 2215, yet that specimen retained a higher tensile strength. The lack of correlation between tensile strength and amount of delamination is not too surprising since stress transfer from layer to layer within the composite can be accomplished by the compressive forces exerted by the tensile testing machine grips. If the test for residual strength had been bending, the results would have been different.

The effect of thermal cycling on transverse specimens was somewhat more severe as indicated in Fig. 19. In this case a distinction was not drawn among specimens from different panels since the as-fabricated strengths were essentially the same. The tests showed that the transverse tensile strength of the angle-ply composites was degraded after cycling to both 260°C and 427°C in a manner which was fairly linear with the number of cycles. As would be expected the higher maximum temperature resulted in a greater reduction of strength.

The specimens underwent both plastic deformation (warping and distortion) and delamination as a result of the thermally-induced stresses caused by the heating and cooling cycles. Figure 20 shows two transverse specimens which had been cycled to 427°C for 500 and 1000 cycles. The extent of visual damage was somewhat greater for the latter. Similar behavior was observed in Ref. 1 for unidirectional materials tested in the transverse direction. In that study transverse specimens were so badly distorted after being cycled to 427°C that they were not tested to measure residual tensile strength. The angleply configuration appeared to improve this behavior.

Although the reduction in off-axis strength of the angleply composites was fairly large, the problems of distortion and delamination under the 427°C conditions may be more significant. In general, loads in off-axis directions are not significant in structural applications, so a loss in strength in those directions may not be critical. However, distortion or delamination of a structure such as a gas turbine engine fan blade would be unacceptable. This implies that the material, in its present state of development, would not be suitable for such applications where the blade was cycled between ambient temperature and 427°C. This is not too surprising since the aluminum matrix is generally not considered for applications at that temperature.

On the other hand the thermal fatigue tests did not indicate any serious problems in the 260°C tests. Although the transverse strength was reduced somewhat, the specimens did not suffer significant dimensional changes, and the longitudinal properties were not greatly affected. This temperature is also more in line with generally accepted upper temperature limits for aluminum alloys.

EFFECT OF THERMAL CYCLING ON LONGITUDINAL SPECIMENS

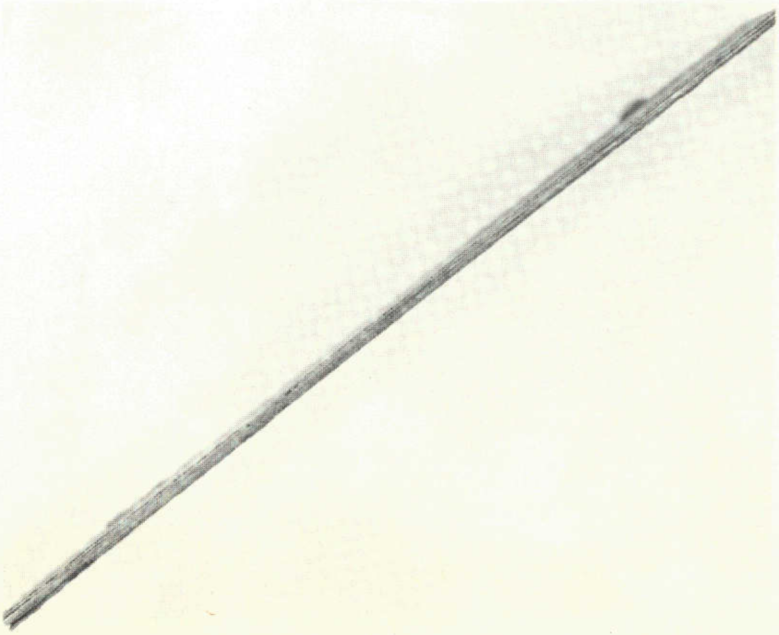
NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

$[(\pm 45)/(0)_4/(\mp 45)]_T$

1000 CYCLES FROM 23°C TO 427°C

NO. 2215–L7

RESIDUAL STRENGTH = 0.327 GN/m^2 (47.5 ksi)



NO. 2264–L7

RESIDUAL STRENGTH = 0.310 GN/m^2 (45.0 ksi)

FIG. 19

EFFECT OF THERMAL CYCLING ON ROOM TEMPERATURE TRANSVERSE TENSILE STRENGTH

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

$[(\pm 45)/(0)_4/(\pm 45)]_T$

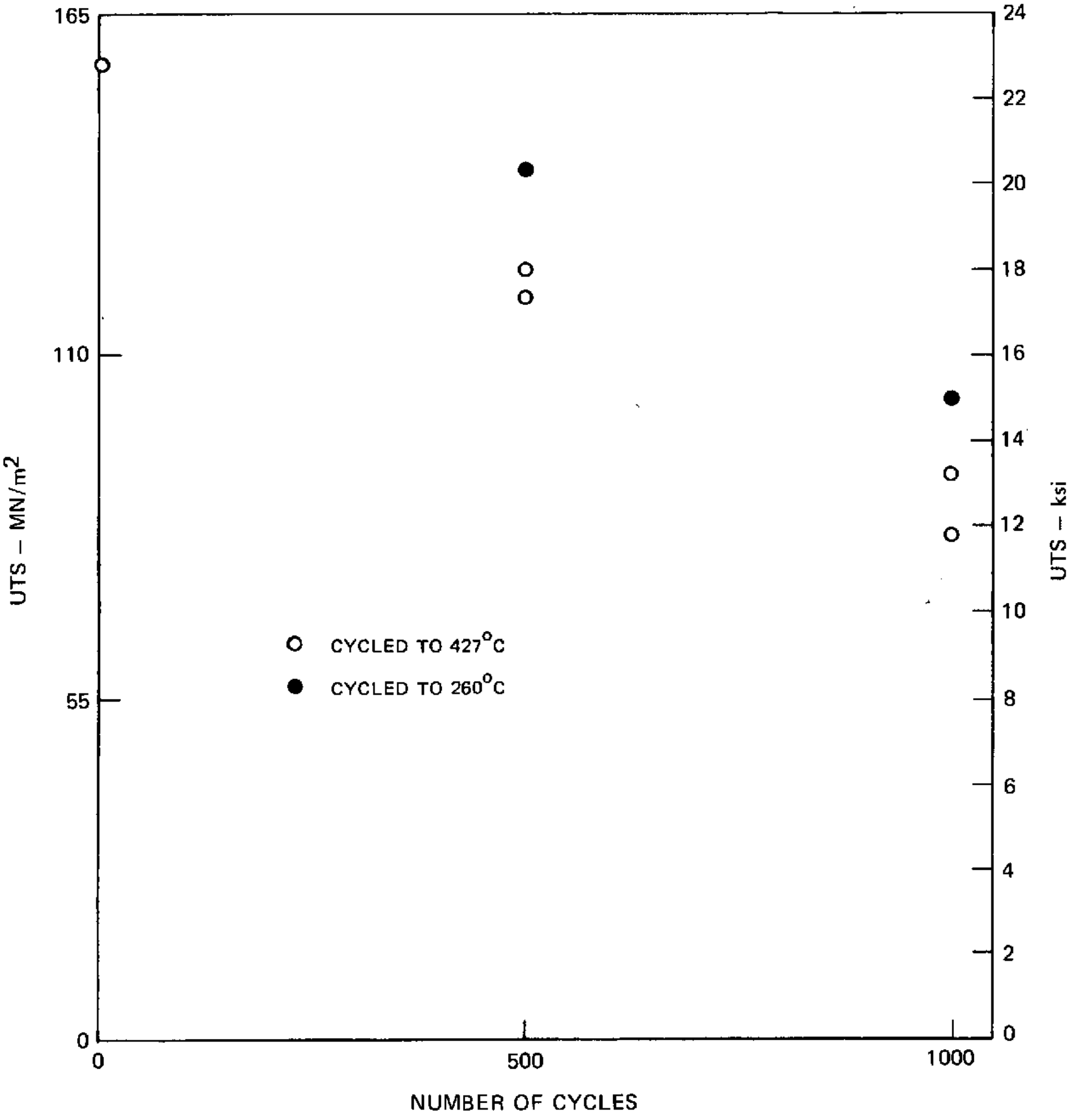


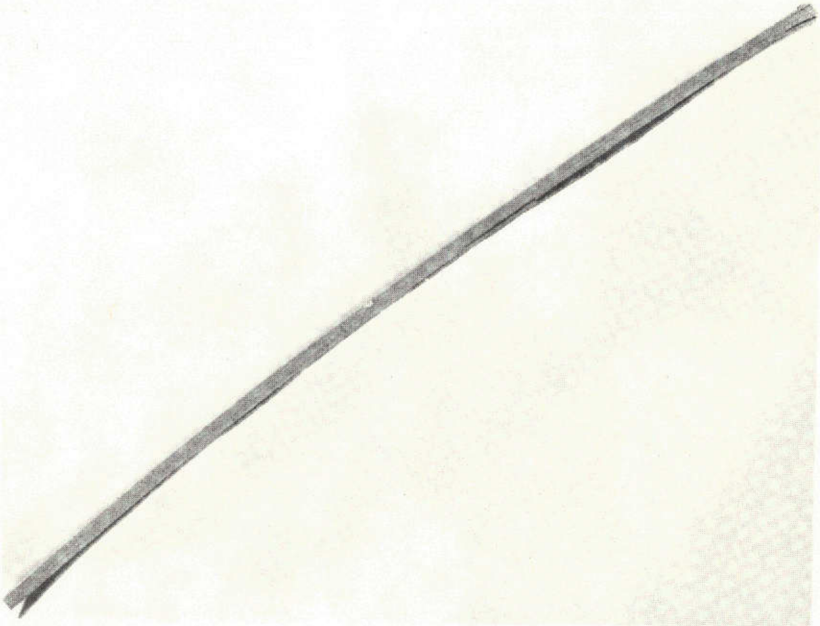
FIG. 20

EFFECT OF THERMAL CYCLING ON TRANSVERSE SPECIMENS

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

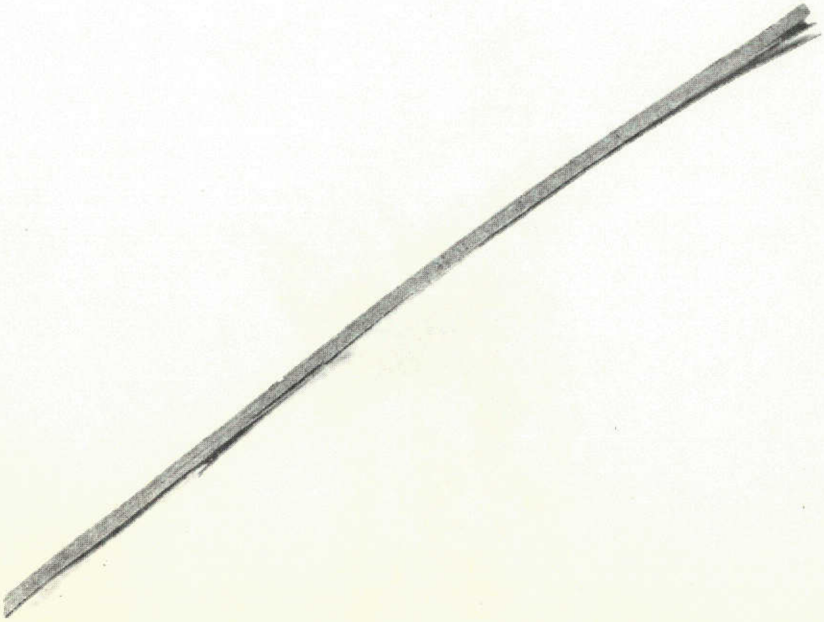
$[(\pm 45)/(0)_4/(\mp 45]_T$

CYCLED FROM 23°C TO 427°C



NO. 2215–T5 500 CYCLES

RESIDUAL STRENGTH = 124 MN/m^2 (18.0 ksi)



NO. 2215–T6 1000 CYCLES

RESIDUAL STRENGTH 81.3 MN/m^2 (11.8 ksi)

N06–60–2

6.5 Impact

6.5.1 Experimental Procedure

Izod impact tests were conducted on two angleply composites reinforced with 3.2 mil NASA-Hough filament of slightly different modulus. The standard filament used throughout other portions of the program had a tensile modulus of 193 GN/m^2 (28 msi), while the other filament had a modulus of approximately 152 GN/m^2 (22 msi). All specimens were "miniature" in that the thickness was reduced from that of the standard specimen. The actual thicknesses ranged from 0.216 cm to 0.284 cm (.085 in. to .112 in.). Other dimensions were standard, i.e. 6.35 cm long x 1.25 cm wide (2.5 in. x .5 in.). Notch depth was .25 cm (.1 in.). Specimens were notched and impacted on edge. Ply configuration was $[(\pm 45)_3/(0)_{12}/(\mp 45)_3]_T$ for all specimens.

6.5.2 Results and Discussion

The impact data are listed in Table IX. The energies were considerably lower than those reported in Ref. 1 for unidirectional composites, where values ranging from 6.8 j/cm^2 to 22.4 j/cm^2 (380 $in\text{-}lbs/in^2$ to 1245 $in\text{-}lbs/in^2$) were measured for materials having a filament volume fraction of 38 percent. The angleply composites might be expected to be somewhat lower in impact energy since the 45° plies could not carry much load in tension or shear in the way in which they were struck. However, a major reason for the lower impact strength of the angleply composites was probably the fact that no delamination occurred during fracture, whereas a significant amount occurred with the unidirectional composites. The energy involved in creating the delamination coupled with the blunting of the tensile crack which results, generally means that composites which undergo delamination absorb more energy in a pendulum impact test than those which do not if the fracture behavior is brittle. Figure 21 is a photomacrograph of the fracture surface of one of the angleply composites, and clearly reveals that the fracture was brittle. In addition there was very little fiber pullout which, along with the lack of delamination, points to a good bond between the filaments and the matrix. It has been found possible to achieve high impact strength in boron-aluminum composites having high interfacial strength (Ref. 4), but high strength (3.45 GN/m^2 - 500 ksi) large diameter (.0142 cm, 5.6 mil) filament were required in order to heavily work the matrix during loading. It appears that the strength and size of the 3.2 mil NASA-Hough monofilament are not sufficient to take advantage of this energy absorbing mechanism. The 5.6 mil filament should result in some improvement, but a larger improvement could be expected through an increased filament strength.

Table IX

Izod Impact Data
NASA-Hough Monofilament/2024 Aluminum
$[(\pm45)_3/(0)_{12}/(\mp45)_3]_T$

	Filament	V_f	Total Impact Energy		Thickness		Energy per Area	
No.	Type	%	joules	(in-lbs)	cm	(in)	joules/cm^2	(in-lbs/in^2)
2269-1	high mod.	40	1.02	9	.285	.112	3.58	202
2269-2	high mod.	40	0.68	6	.285	.112	2.13	120
2291-1	low mod.	43	0.68	6	.254	.100	2.68	151
2291-2	low mod.	48	0.68	6	.216	.085	3.15	178

IZOD IMPACT FRACTURE SURFACE

NASA–HOUGH MONOFILAMENT/2024 ALUMINUM

$[(\pm 45)_3/(0)_{12}/(\pm 45)_3]_T$

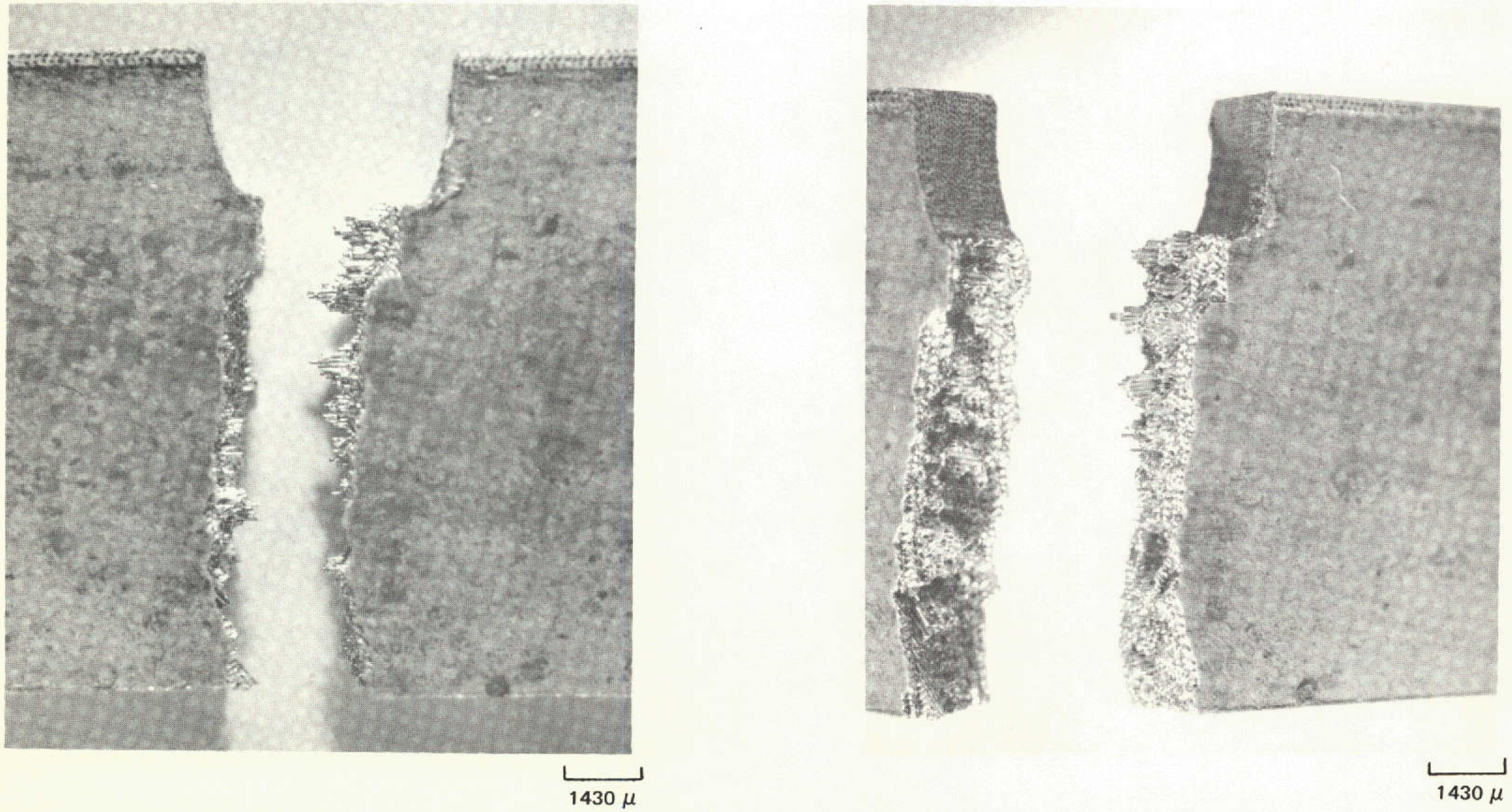


FIG. 21

VII. CONCLUSIONS

1. Angleply composites of NASA-Hough monofilament/2024 aluminum can be fabricated such that excellent translation of filament tensile strength can be achieved.

2. Elevated temperature tensile tests indicate that the material has good retention (80%) of room temperature tensile strength at 260°C. At 427°C approximately 60 percent of the room temperature strength is retained.

3. Stress-rupture and creep testing in the longitudinal direction at 260°C showed very little effect of time on the tensile strength of the material. At a test temperature of 427°C the long term effects become more noticeable and the material would not be satisfactory in structural applications involving long times under stress at that temperature.

4. Bending fatigue life of the material is controlled by a delamination failure mode which results in progressive loss of specimen stiffness with increasing stress or number of cycles. The endurance limit for a 90 percent retention of initial modulus is approximately 69 MN/m^2 (10 ksi).

5. Thermal cycling between room temperature and 260°C has no significant effect on longitudinal composite strength, and causes only minor reduction in transverse strength. Cycling to 427°C reduces the longitudinal tensile and transverse tensile strengths and causes distortion of the specimens which would be unacceptable in many applications.

6. Izod impact strengths are fairly poor and were appreciably under the values obtained for uniaxial specimens.

REFERENCES

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3. Structural Design Guide for Advanced Composite Applications, Vol. 1, Material Characterization, Jan. 1971.

4. K. Prewo, "The Charpy Impact Energy of Boron-Aluminum", J. Comp. Matl's., Vol. 6, Oct. 1972.