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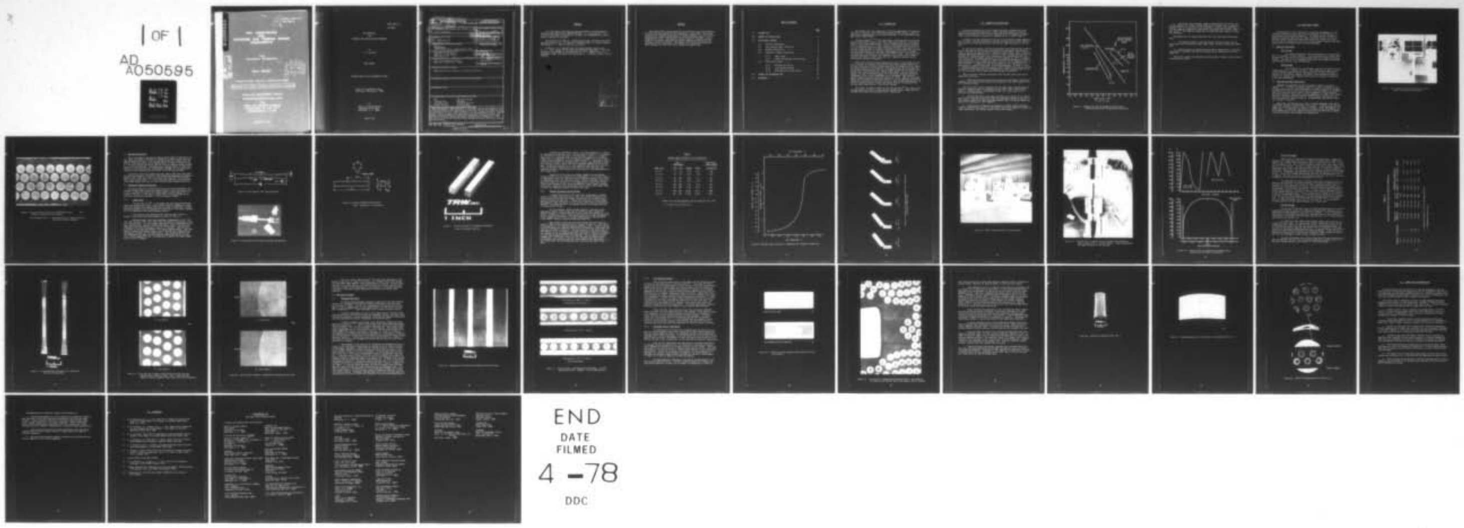

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FRS COMPOSITES FOR ADVANCED GAS TURBINE ENGINE COMPONENTS

TRW
MATERIALS TECHNOLOGY

FINAL REPORT

Prepared Under Contract N62269-76-C-0355

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER,PENNSYLVANIA 18974
FOR
NAVAL AIR SYSTEMS COMMAND
DEPARTMENT OF THE NAVY
WASHINGTON,D.C. 20361

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By

W. D. Brentnall

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Continued property characterization & fabrication process development of fibe reinforced superalloy (FRS) composites is described. The current investigations included determination of impact toughness, low cycle fatigue properties & thermal fatigue behavior of angle plied specimens in the W-1ThO2/FeCrAlY system. Additionally, process feasibility studies were performed in the areas of monotape fabrication, secondary bonding and hollow simulated airfoil fabrication. The feasibility of using the Pre-consolidated monotape FRS blade fabrication process was demonstrated.

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FOREWORD

This final report describes the work performed for the Department of the Navy under NADC Contract N62269-76C-0355. It is published for information only and does not necessarily represent the recommendations, conclusions or approval of the Navy.

This contract with TRW Inc., 23555 Euclid Avenue, Cleveland, Ohio 44117 was performed with Mr. Irvin Machlin, AIR-52031B, Naval Air Systems Command, Washington, D. C. 20361 as technical consultant.

At TRW, Mr. W. D. Brentnall was the program manager reporting to Dr. I. J. Toth, Manager of the Materials Development Department. Other TRW personnel contributing to the program were Mr. M. R. Cooney and Mr. L. E. Chojnowski, panel fabrication and testing and Mr. J. Sweeney, thermal fatigue testing.

ABSTRACT

Continued property characterization and fabrication process development of fiber reinforced superalloy (FRS) composites is described. The current investigations included determination of impact toughness, low cycle fatigue properties and thermal fatigue behavior of angle plied specimens in the W-1ThO_2/FeCrAlY system. Additionally, process feasibility studies were performed in the areas of monotape fabrication, secondary bonding and hollow simulated airfoil fabrication. The feasibility of using the pre-consolidated monotape FRS blade fabrication process was demonstrated.

TABLE OF CONTENTS

1.0 INTRODUCTION

The objective of this program was to continue development of oxidation/sulfidation resistant fiber reinforced superalloy (FRS) systems, capable of operating as advanced gas turbine engine components in the temperature range 982°-1315°C (1800°-2400°F).

Previous programs(1),(2) had identified a W-1ThO_2/FeCrAlY system which, based on preliminary property data, has considerable potential for advanced engine turbine blade applications. This first generation system has potential for operating at up to 1148°C (2100°F) metal temperatures and exhibits up to a threefold specific strength advantage (100-hour creep rupture) over the best competing metallic systems, oxidation/corrosion resistance such that protective coatings are not required, and adequate resistance to thermal cycling based on 1000-cycle 27°-1204°C (80°-2200°F) tests. Preliminary cost estimates have also indicated that components such as FRS turbine blades could be fabricated at lower costs than other competing systems, such as directionally solidified eutectics.

The current work was aimed at generating certain critical data that are still required for component selection and preliminary design analyses and included impact and low cycle fatigue properties for composites with uniaxial and various angle-ply reinforcements. Some experiements were performed that were aimed at demonstrating that current composite fabrication methods could be applied to the fabrication of complex blade shapes in a cost effective manner. The use of preconsolidated, fully densified, composite monolayers (monotapes) offers certain advantages for the subsequent fabrication of complex shapes with controlled distributions of fibers. Some critical experiments were performed to demonstrate feasibility of the monotape fabrication method for the production of hollow airfoils. Both of these evaluations, the property characterization studies, and process feasibility demonstrations were performed concurrently in the current program.

This report includes a summary of the previous work(3) and a description of experimental activities in the areas of thermal fatigue, impact testing, monotape fabrication and simulated airfoil fabrication.

2.0 SUMMARY OF PREVIOUS WORK

The continuing objective of this program has been to develop an oxidation/corrosion resistant metal-matrix fiber reinforced composite system designed for advanced gas turbine engine components which are capable of operating, without a protective coating, at temperatures up to 1200°C (2400°F).

A FeCrAlY alloy was selected for the matrix alloy based on known properties which included: excellent oxidation/corrosion resistance up to 1370°C (2400°F), good ductility, a high melting point, low density, good fabricability and low cost.

In the initial program, fabrication parameters were developed and screening studies performed using a variety of potential reinforcements, including SiC, Al_2O_2, W and Mo, and reaction barrier coated refractory metal fibers. Based on elevated temperature compatibility, preliminary stress rupture data and cost and availability, refractory metal wires (tungsten alloy, molybdenum alloy) were identified as having greatest potential as reinforcements for the first generation FRS systems. A W-1Tho_2/FeCrAlY composite system was subsequently shown to have potential long term (>1000 hour stress rupture) life at temperatures up to 1150°C (2100°F). A comparative specific strength plot for superalloys, 1st generation D.S. eutectics and fiber reinforced superalloys, is shown in Figure 1. Extended temperature capability beyond 1150°C (2100°F) would require the use of reaction barrier coatings and thermodynamically stable carbides such as TiC, TaC, HfC were identified as promising diffusion barrier coatings.

Some of the more important conclusions from the most recent work may be summarized as follows:

1. Composite properties and structure were not significantly affected by repeated rapid thermal cycles between room temperature and 1204°C (2200°F) for up to 1000-cycle tests.

Very high stress rupture strengths and low creep rates were obtained with W/FeCrAlY composites over the temperature range 1037°-1148°C (1900°-2100°F). Specific strengths (density normalized) of over 2-1/2 times those of D.S. eutectics were demonstrated.

3. Oxidation/corrosion resistance was shown to be typical of the FeCrAlY matrix alloy since the reinforcing fibers are completely encased by the matrix. The oxidation penetration rate along edge exposed fibers (simulated damage) was about 0.010 inch/hour at 1204°C (2200°F).

4. Tensile tests on angle-plied composites at 649°C (1200°F and 760°C (1400°F) indicated that a ±15° ply construction would have adequate strengths at these temperatures to withstand typical blade root stresses.

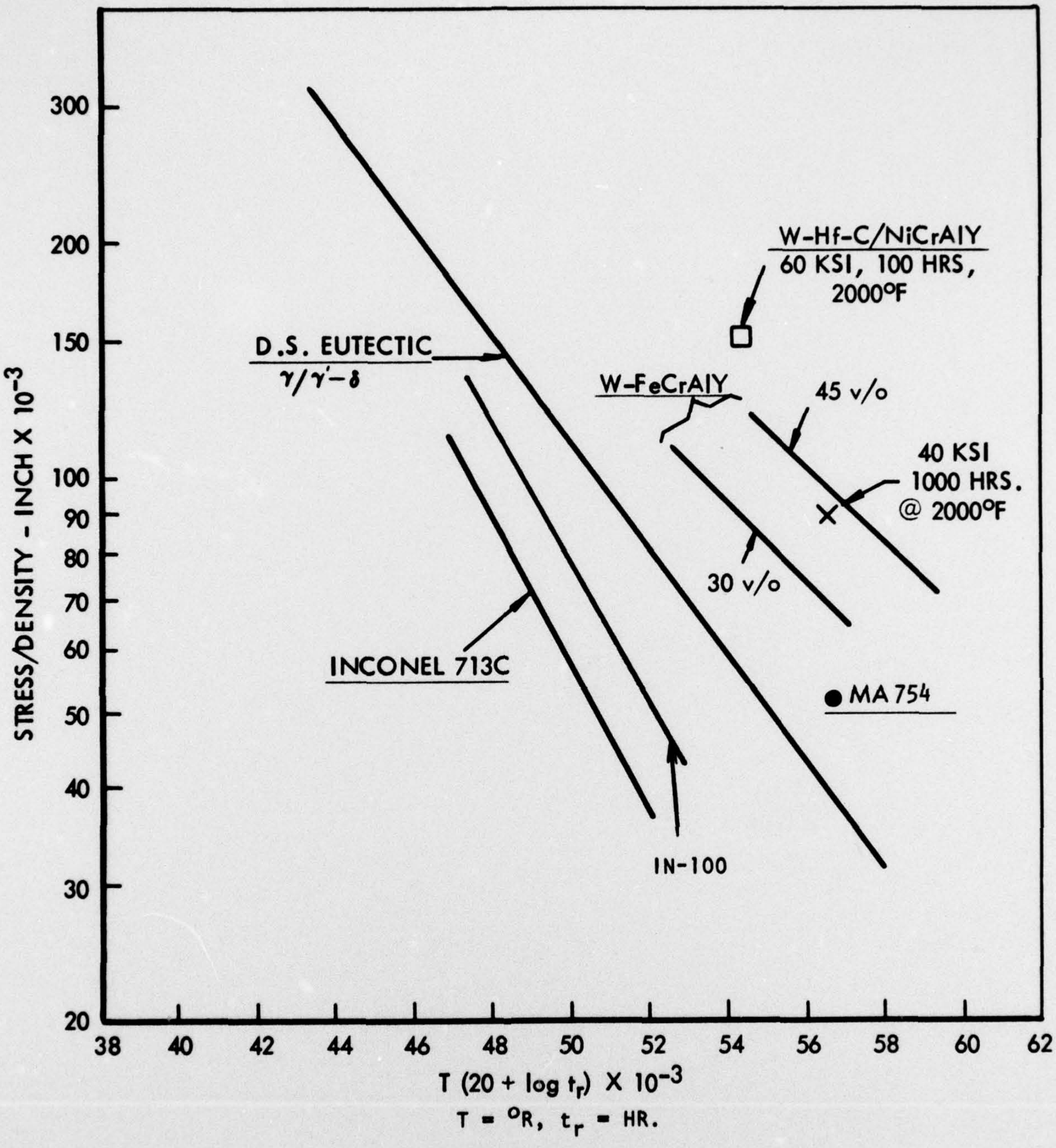


Figure 1. Comparative, Density Normalized Larson-Miller Stress-Rupture Curves (Longitudinal Properties).

5. Preliminary cost estimates, based on extrapolations of current fabrication methods, for a model turbine blade having internal cooling channels, selected fiber distributions and root attachment, indicate a per blade cost in the same range as conventional directionally solidified (polycrystal) blades. A more recent(4) cost modeling program has provided additional support to these cost estimates.

Recommendations for needed additional work with these promising systems were:

1. More advanced property characterization including thermal cycling tests under static and dynamic loads, shear creep, low cycle fatigue and impact tests.

2. Process feasibility demonstrations aimed at identifying or confirming cost effective component fabrication processes and at demonstration of shape capability.

The current program was designed to develop some of these critical property and fabricability data.

3.0 EXPERIMENTL PROGRAM

The objectives of this program were to continue development of fiber reinforced superalloy composites which are designed for application as advanced gas turbine engine components. The program was not designed to develop an extensive data base but rather to perform certain critical experiments aimed at developing additional preliminary property and fabricability data to indicate the viability of these systems. Results from these experiments are discussed in the following paragraphs.

3.1 Material Procurement

Matrix Alloy

The nominal composition of the selected matrix is Fe-20-24Cr-5Al-1.0Y (elements in weight percent). This was procured from Federal Mogul Corporation in the form of pre-alloyed powder made by the argon atomization process. The majority of the powder being used on the program was screened into the particle size range -80 +500 mesh.

Reinforcement

The selected fiber reinforcement used for the majority of the program was 0.015 in. diameter W-1ThO_2. This represented a readily commercially available material and may be procured from at least two vendor sources. For the current program, this material was procured from General Electric to standard lamp filament specifications in terms of surface condition and straightness.

3.2 Test-Specimen-Panel-Fabrication

Fabrication procedures have been discussed in detail in previous reports(1-3). In brief, the process consists of fiber collimation by drum winding, converting the pre-alloyed powder to sheets of specified thickness and density by use of a fugitive plasticizer, and consolidation of assembled layers of fibers and matrix cloth by inert atmosphere diffusion bonding. For these materials, typical hot pressing parameters are 1000°-1120°C (1850°-2050°F) at 140-207 M Pa (20-30 ksi) for 30-90 minutes. Molybdenum alloy dies were used with induction heating. An experimental hot pressing facility is shown in Figure 2.

Good fiber distributions with a fairly uniform hexagonal array and no fiber/fiber contacts are obtained by this process. A typical cross section taken from a previous report is shown in Figure 3. Other advantages of this process are: 1) almost any desired matrix composition may be selected and 2) no degradation of fiber properties occurs since the fabrication temperatures are no higher than projected use temperatures.

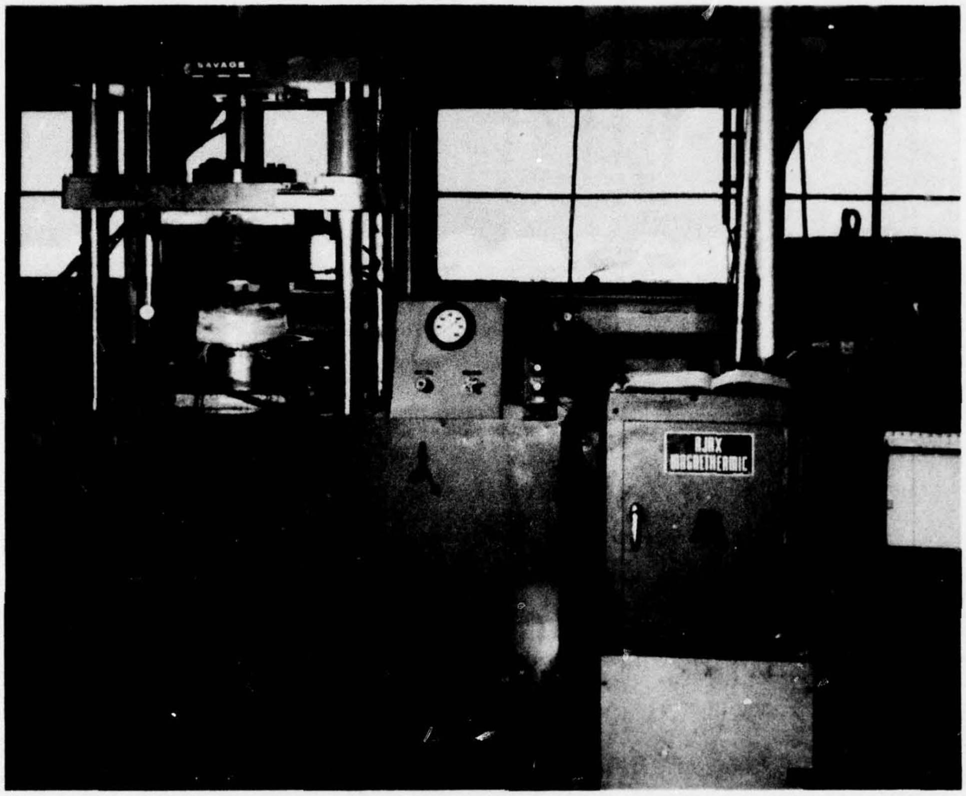


Figure 2. High Temperature Diffusion Bonder Used For Superalloy Composite Fabrication.

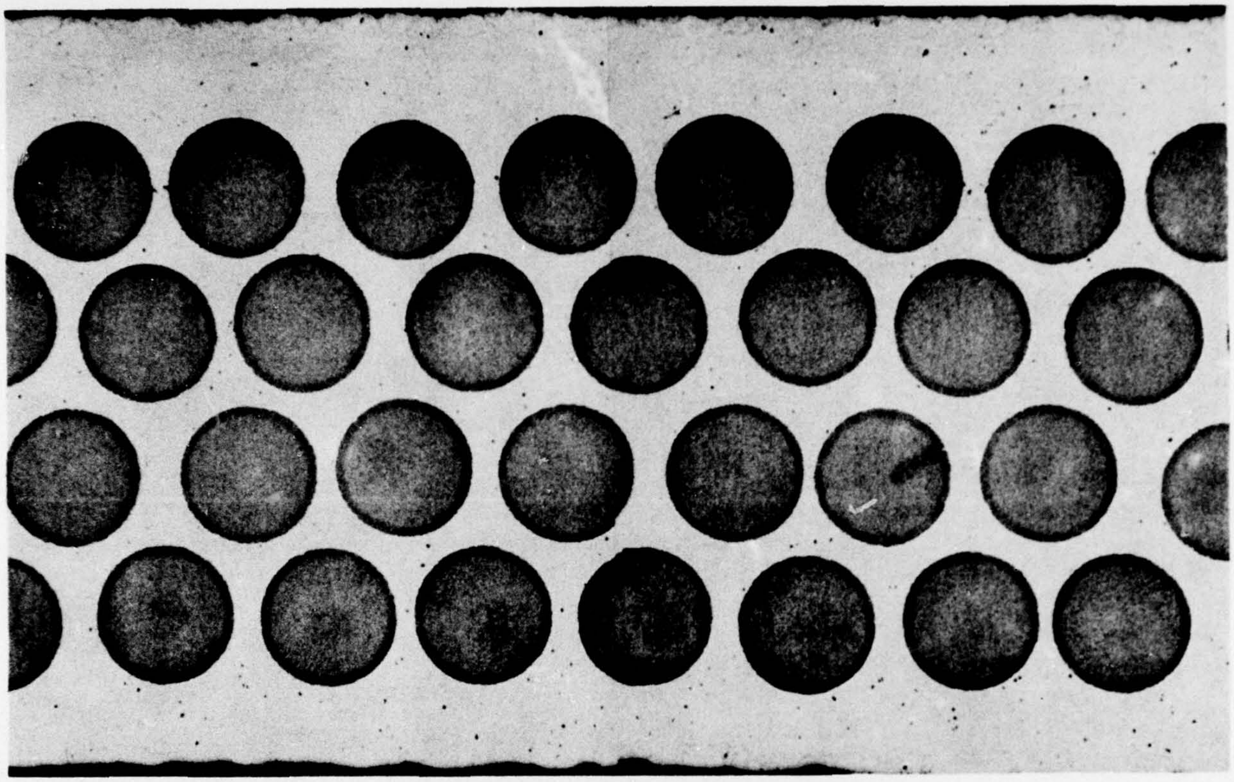


Figure 3. Typical Microstructure of $W\text{-}1ThO_2/FeCrAlY$ Panel 50X
Showing Uniform Fiber Distribution

Reinforcement Level ∿ - .60 Volume Fraction (Packing Density)
- .30 Volume Fraction (Overall).

3.3 Specimen Fabrication

Since the composite fabrication process lends itself to fabrication of flat sheet type panels, specimens for mechanical property evaluations have been designed accordingly. The specimen design and grip assembly used for tensile, creep and stress rupture determinations is shown in Figures 4 and 5. A similar specimen design was used for the instrumented thermal fatigue tests (low cycle fatigue). The wedge action loading results in shear load transfer to the fibers and may be considered analogous to the anticipated load distribution between root and airfoil in an FRS turbine blade.

Conventional machining methods have been used to fabricate these specimens with the exception of specially fabricated specimens having completely encased fibers which were used in the previously reported(2,3) air atmosphere stress rupture tests. In this latter case electrical discharge machining (EDM) methods were used to avoid residual-stress-induced distortion.

3.4 Mechanical Property Evaluations

Additional mechanical property evaluations that were conducted on this program included impact tests and thermal fatigue - low cycle fatigue tests. It was not possible to perform the planned shear strength evaluations in time for inclusion in this report. These tests will be performed on the follow-on contract and reported in the first Quarterly Report.

3.4.1 Impact Tests

From previous work(5), it was known that the tungsten-reinforced superalloy systems have a fairly well defined transition temperature range where the toughness can change by more than an order of magnitude. No data had been developed on the W-1ThO$_2$/FeCrAlY system which is currently regarded as a first generation FRS blade candidate material.

The miniature Izod specimen design that was used is shown in Figure 6, and typical machined specimens are shown in Figure 7.

Pendulum impact tests were performed at temperatures of 21°, 65°, 149°, 260° and 371°C (70°, 150°, 300°, 500° and 700°F) using notched, miniature Izod specimens. For the elevated temperature tests, thermocouples were spot welded onto the specimen surface within about 1.5mm of the notch and temperature monitored continuously using an X-Y recorder. Specimens were positioned in the grips and heated in situ using propane burners. They were heated to about 25-50 degrees higher than the desired test temperature and the pendulum released on the cooldown cycle. This procedure ensured that the thermocouple was measuring bulk specimen temperature and not a transitory surface temperature, and it was possible to control the impact temperature to within 2 degrees.

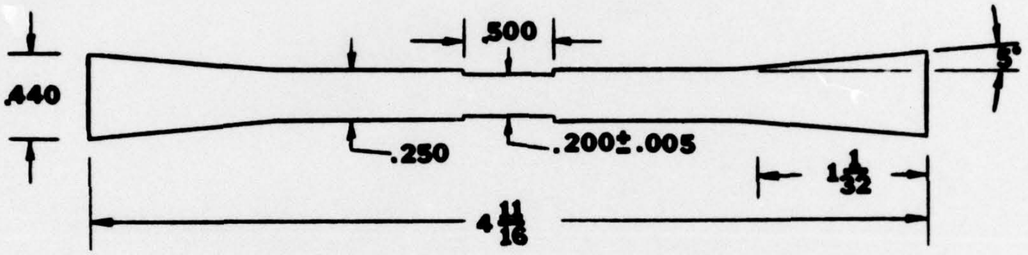


Figure 4. Stress Rupture Test Specimen Design.

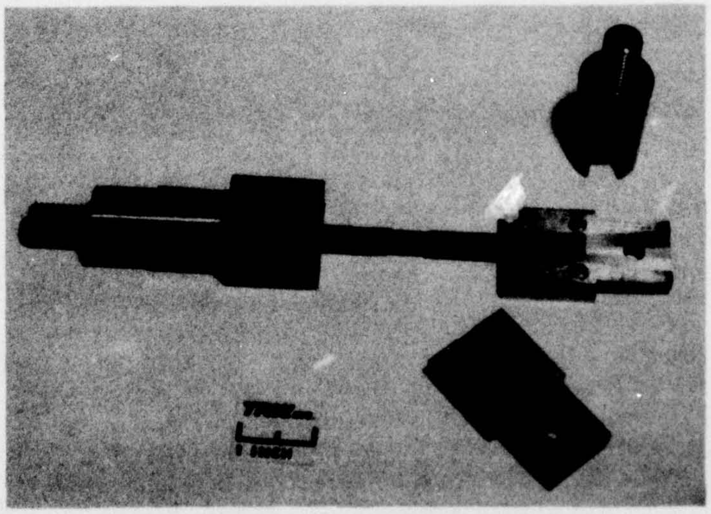


Figure 5. Stress Rupture Grip Assembly and Machined Specimen.

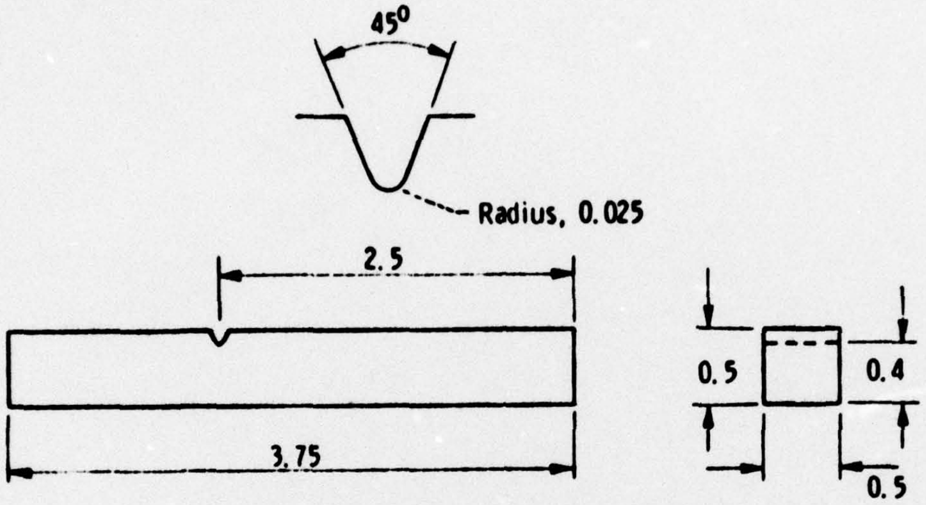


Figure 6. Miniature Notched Izod Specimen.
Note: Dimensions in Centimeters.

Figure 7. Miniature Notched Izod W/FeCrAlY Specimens. Note Thermocouple Location.

The data are tabulated in Table I and shown graphically in Figure 8. Representative specimens after test are shown in Figure 9. A pronounced ductile/brittle transition range is indicated from Figure 9 in the 200°C range which is in agreement with the data on 218 tungsten wire reinforced nickel alloys developed on an earlier NASA contract(5). The current data on W-1ThO$_2$/FeCrAly composites indicate slightly higher room temperature toughness and significantly higher 250°-370°C toughness compared to the earlier data. Normalizing the data for a cross sectional area equivalent to a full size Izod specimen (neglecting any size effects) would indicate impact strengths of about 3 foot pounds and 53 foot pounds at room temperature and 370°C respectively.

Inspection of the fracture surfaces revealed the anticipated fracture behavior of the tungsten wire reinforcement, i.e, brittle fracture at temperatures below the transition and considerable necking of the fibers at temperatures above the transition range. Fracture toughness therefore is controlled mostly by the matrix at low temperatures so that lower volume fraction reinforcement levels would correspond to higher impact strengths, while higher volume fraction reinforcement levels would yield higher impact strengths at temperatures above the transition range.

3.4.2 Thermal Fatigue/Low Cycle Fatigue

In composite materials with significant differences of thermal expansivity between fibers and matrix, the terms thermal fatigue and low cycle fatigue are perhaps more closely related than in the case of macroscopically monolithic materials. Thermal cycling alone, of unrestrained specimens can cause substantial cyclic plastic strains and as discussed by Garmong(6) can cause the matrix to undergo constant-strain-amplitude tension-compression fatigue.

For this program, thermal fatigue testing is defined as high-temperature thermal cycling under zero or relatively small externally applied stresses to simulate blade hot section conditions whereas low cycle fatigue is defined as load or strain-controlled cycling under isothermal or cyclic temperature conditions, with peak temperatures in the 500°-760°C (1100°-1400°F) range to simulate blade root conditions.

Both thermal fatigue and low cycle fatigue tests have been conducted in TRW's Gilmore testing facility (Figures 10 and 11), which can be pre-programmed for any combined temperature/stress cycles. Typical thermal cycles and temperature gradients existing during testing of these sheet type specimens are shown in Figure 12. The cooling rate is limited by rate of heat removal to the surroundings and water cooled grips whereas the heating rate depends on the programmed power input and could, in fact, be arranged to cause instantaneous melting of the specimen. The two thermal cycles schematically illustrated in Figure 12 are intended to simulate engine start-engine stop cycles and the less severe take-off and land cycles. In the current work, the room temperature to T max cycle was used for most tests.

TABLE I

Notched Impact Strengths of W-1ThO$_2$/FeCrAlY

Spec. I.D.	Test Temperature °C	Test Temperature °F	Joules	In-Lb	Normalized Impact Energy In-Lb/In^{2*}
F2-11-1	21	70	2.67	10.3	332
F2-11-2	21	70	2.20	8.5	274
F2-11-3	66	150	2.93	11.3	364
F2-11-4	66	150	3.40	13.1	422
F2-11-5	149	300	5.45	21.0	677
F2-11-6	149	300	5.48	21.5	693
F2-11-7	260	500	36.88	142.0	4580
F2-11-8	371	700	41.68	160.5	5177

* Based on an Average Specimen Area of 0.200 cm^2 (0.31 in^2).

(J - 3.85 in-lb = 0.737 ft-lb.

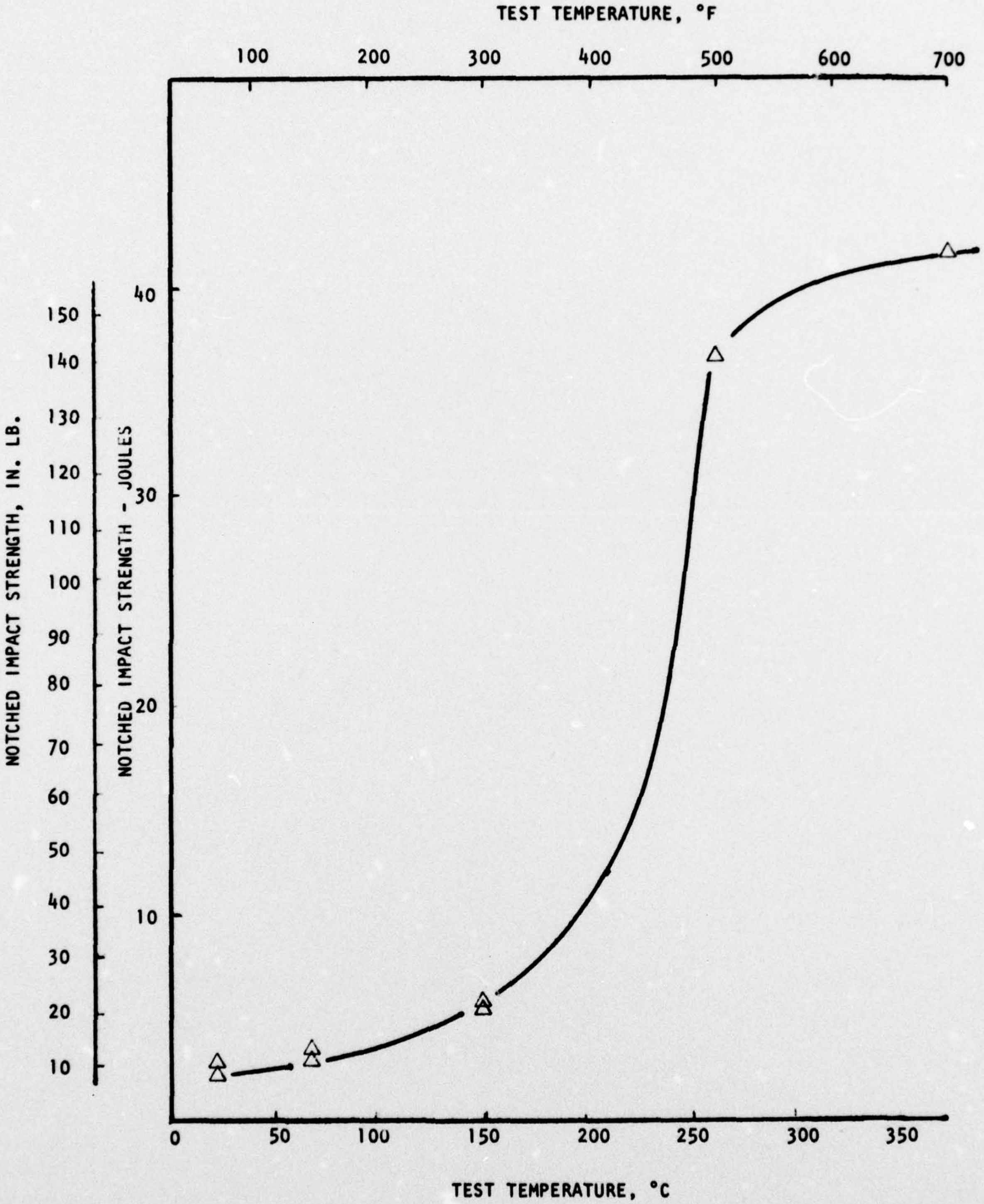
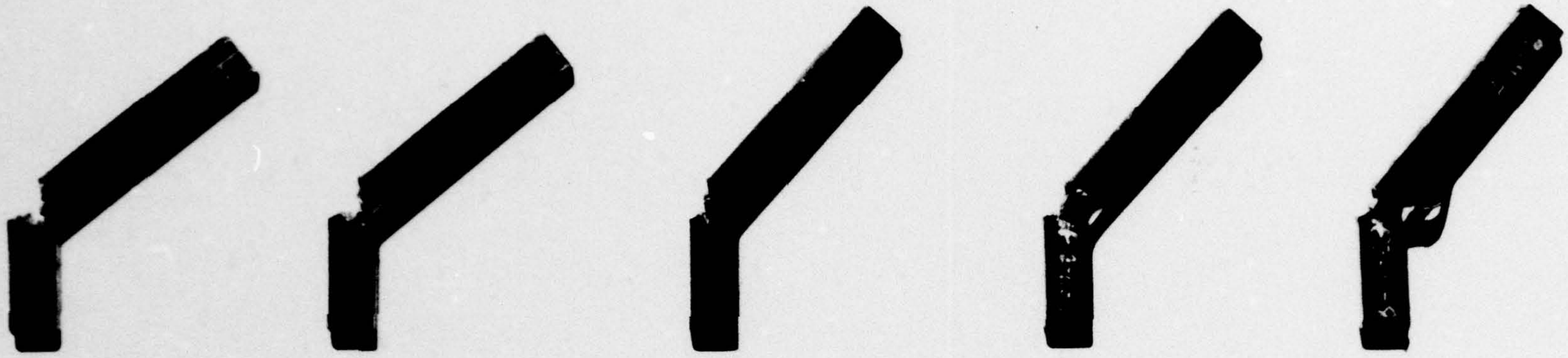


Figure 8. Notched Impact Strength vs Temperature for W/FeCrAlY Composites.



70°F
10.3 in. lb.

150°F
13.1 in. lb.

300°F
21 in. lb.

500°F
142 in. lb.

700°F
160 in. lb.

Figure 9. Notched Izod Impact Specimens After Testing At Indicated Temperatures.

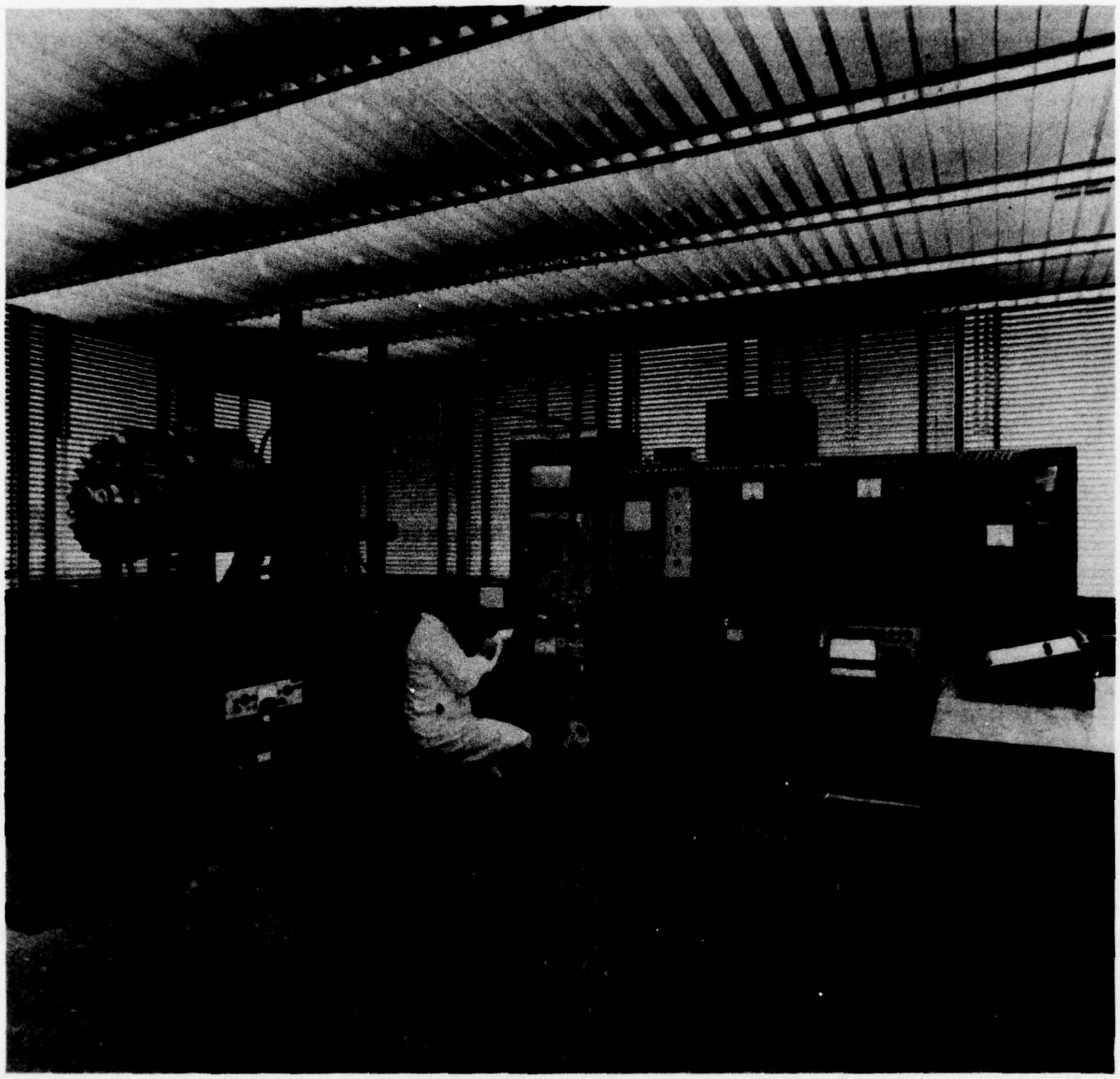


Figure 10. TRW's Gilmore Universal Testing Machine

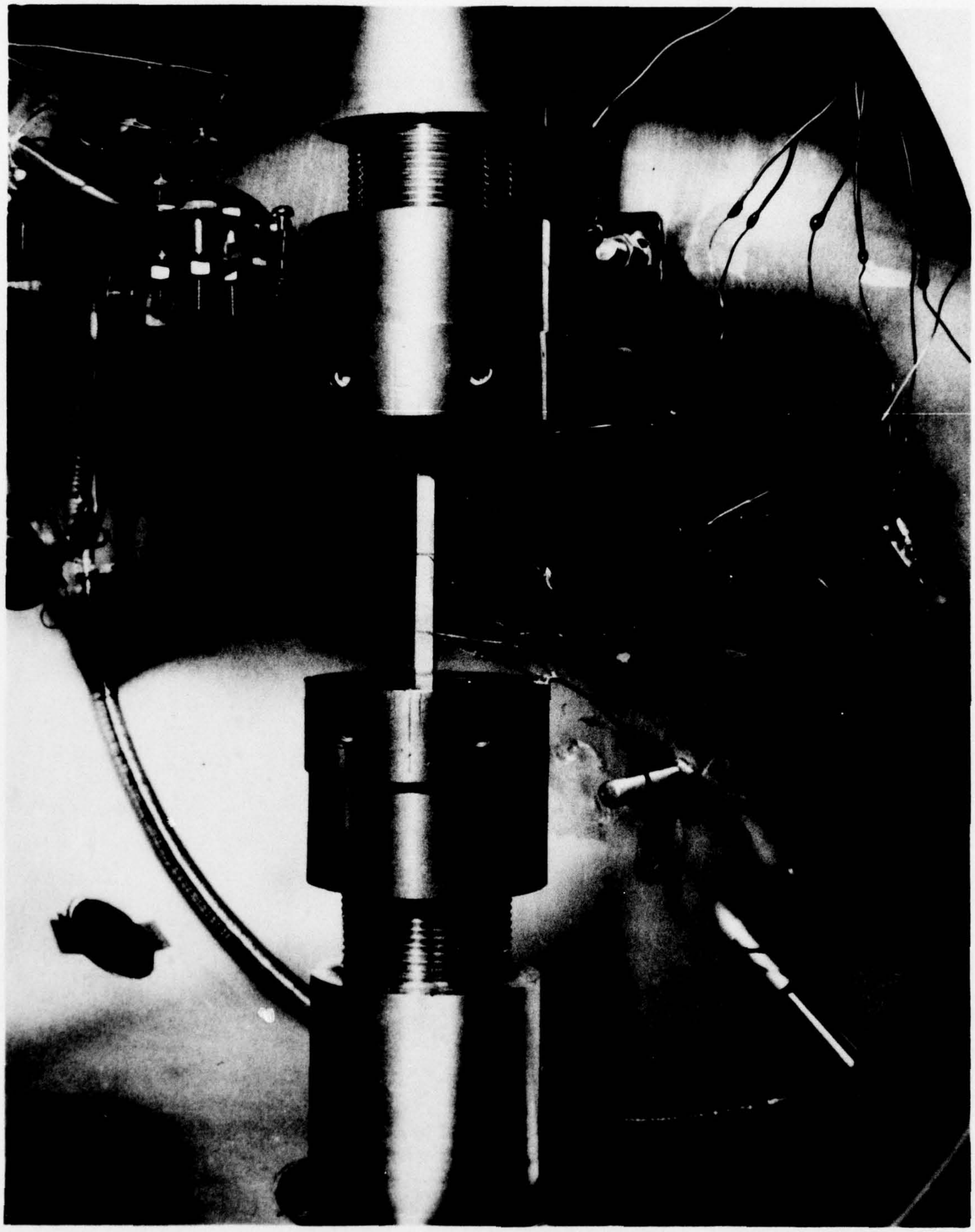


Figure 11. Close-Up View of Thermal Fatigue Specimen Mounted Between Water Cooled Grips in the Test Chamber. Three Thermocouples Are Shown Welded on to the Specimen.

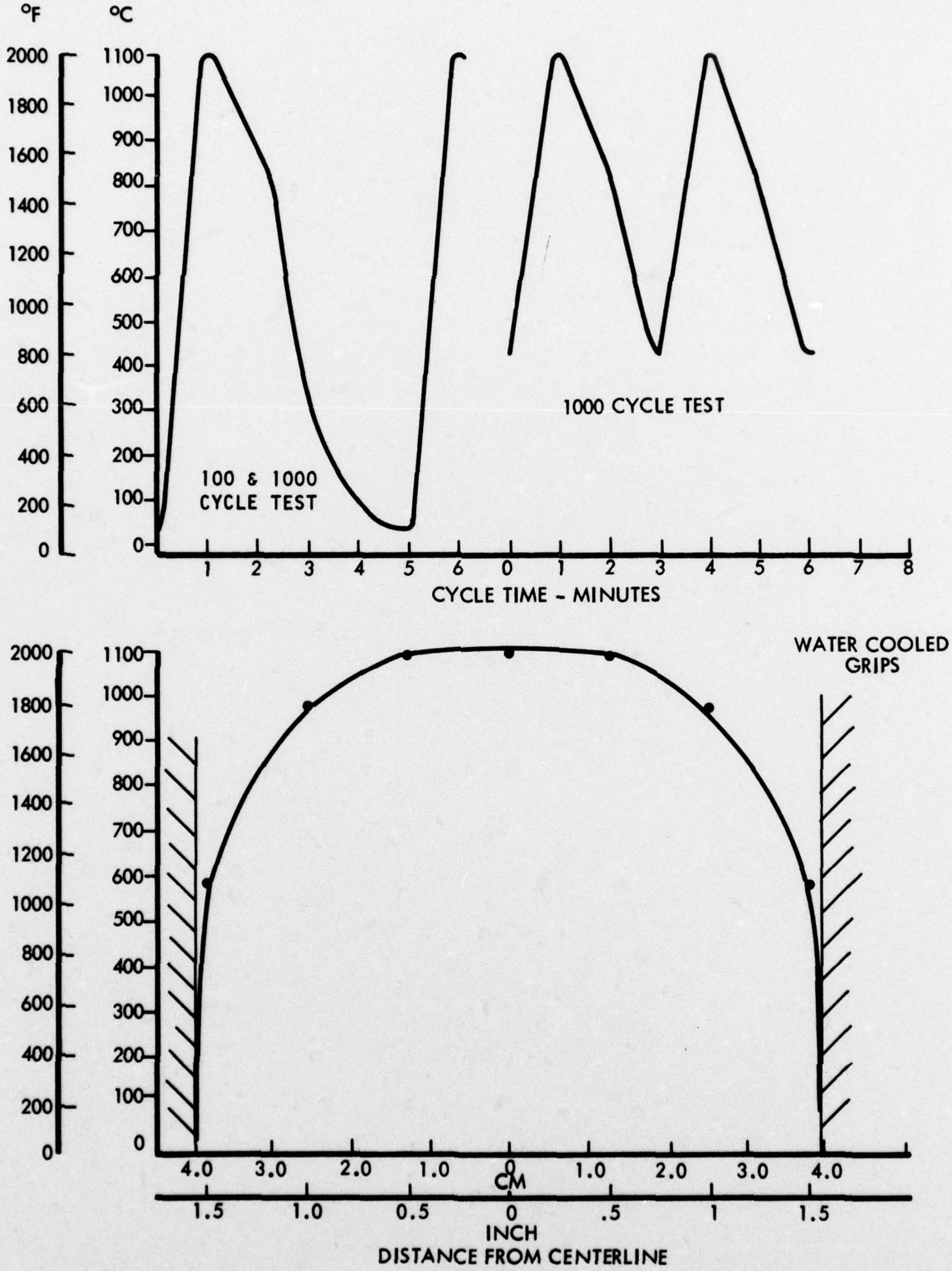


Figure 12. Thermal Cycles and Temperature Gradient Along Specimen During Thermal Fatigue Test.

Low Cycle Fatigue

Preliminary LCF tests were initiated during this work. Tests were conducted with temperature cycles of 21°-649°C (70°-1200°F) and 21°-760°C (70°-1400°F) with in-phase (load controlled), tensile stress cycles 0-σ max. Heating time was about 47 sec. with a linear increasing stress cycle, and a total cycle time of 3.3-3.6 minutes. The goal in these tests was for a total of 1000 cycles. Temperature and stress cycles are identified in Table II along with specimen dimensional change data. One specimen failed prematurely because of thermocouple malfunction. Elongation was monitored optically during test on a 1/2-inch gage section. Width and thickness measurements were made on specimens after test. In general, there was an initial high elongation rate over the first 5-10 cycles followed by a lower rate over the remainder of the test.

The appearance of typical specimens after test is shown in Figure 13. There was no distortion or surface cracking visible after the 1000-cycle tests. Specimen LF-5 which had a ±15° cross-ply fiber orientation showed signs of necking after the 1000-cycle test and was sectioned through the necked region and adjacent to the cooled grip location. Figures 14 and 15 show the metallographic cross sections. As shown in Table II, there was an indicated 13.6% RA in the necked region and from Figure 14, there was an indicated 12.8% reduction of area of the tungsten fibers. It can be observed in Figures 14 and 15 that there was no fiber matrix debonding or internal cracking following this deformation. It should be noted that actual FRS turbine blade design will probably call for mixed orientation, e.g., ±10°, 0°, or ±15%, 0°. It is planned to evaluate specimens of more complex geometries in future work.

Thermal Fatigue

Earlier work(2) had shown that no significant deterioration in tensile properties occurred in uniaxially reinforced W-1ThO$_2$/FeCrAlY specimens after 1000 thermal cycles between 21° and 1200°C (70°-2200°F). It is of considerable importance to investigate the behavior of specimens having fiber distributions representative of potential turbine blade constructions, i.e., a mixed angle-ply construction such as ±15°, 0°.

One additional 427°-1093°C (800°-2000°F) thermal cycle test was performed during this work. The specimen had a fiber orientation of ±15° and was cycled under zero load with a goal of 1000 cycles. The specimen actually ran for 1003 cycles at which time the tack welded control thermocouple broke away resulting in specimen overheating and melting. It was not possible therefore to conduct residual strength determinations and metallography. After 625 cycles, there was no distortion or cracking, and a measured length increase of about 4% over the 1/2-inch gage or overall length increase of 0.42%.

The only conclusions that could be drawn from this test therefore were that the specimen with ±15° fiber orientation appeared to behave similarly to previously tested material with uniaxial 0° fiber reinforcement.

TABLE II

Low Cycle Fatigue Test Data on W/FeCrAlY Composites

Specimen	Orientation	Temperature Range °C	Stress Range	No. of Cycles	Dimensional Change (%)			RA(%)
					Length[1]	Width	Thickness	
LF-1	0	21-760	0-50 ksi	206[2]	-	-	-	-
LF-2	0	21-760	0-40 ksi	1000	2.05	0	-3.8	-3.8
LF-3	0	21-649	0-50 ksi	1001	6.40	-1.3	-8.9	-10.2
LF-4	±15	21-649	0-40 ksi	1000	3.98	-6.6	-1.6	-8.2
LF-5	±15°	21-649	0-50 ksi	1000	16.70	-6.3	-7.3	-13.6
LF-6	0°	21-649	0-60 ksi	1000	0.67	-0.15	-0.02	-0.17

1 - Measured Optically on 1/2-inch Gage Section.

2 - Thermocouple Malfunction.

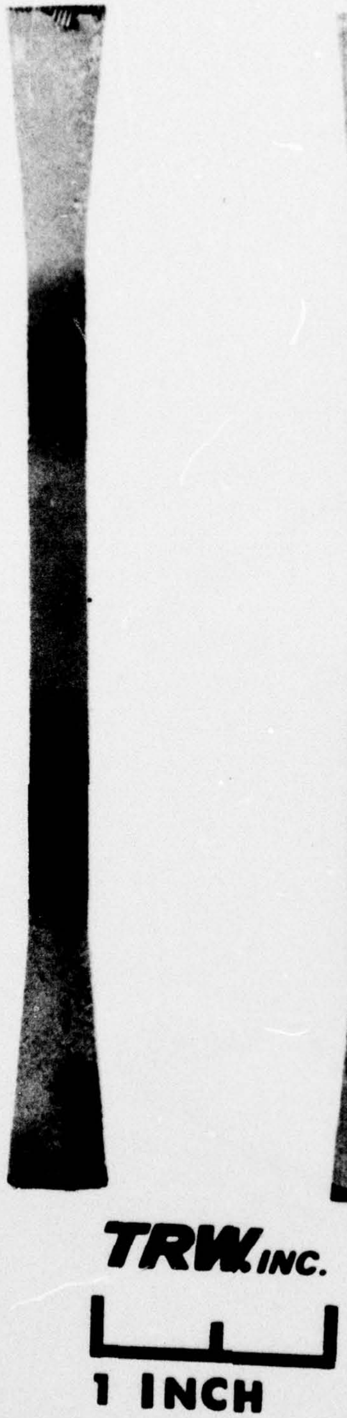
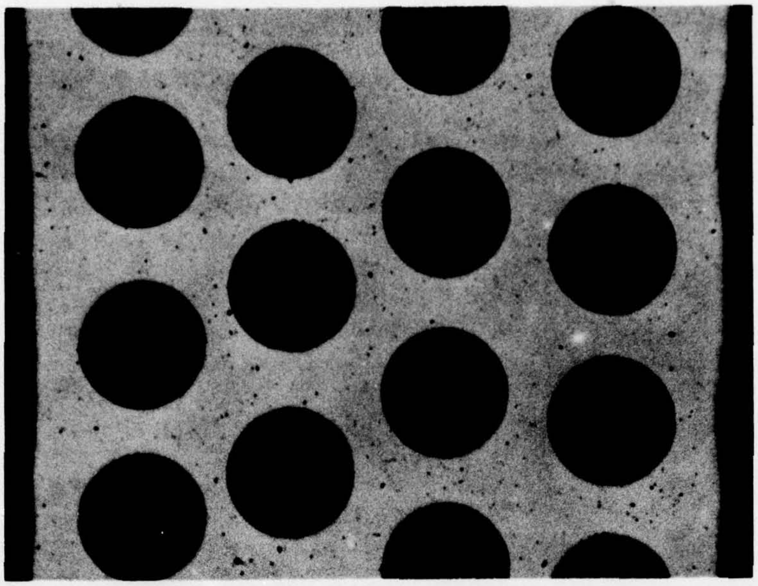
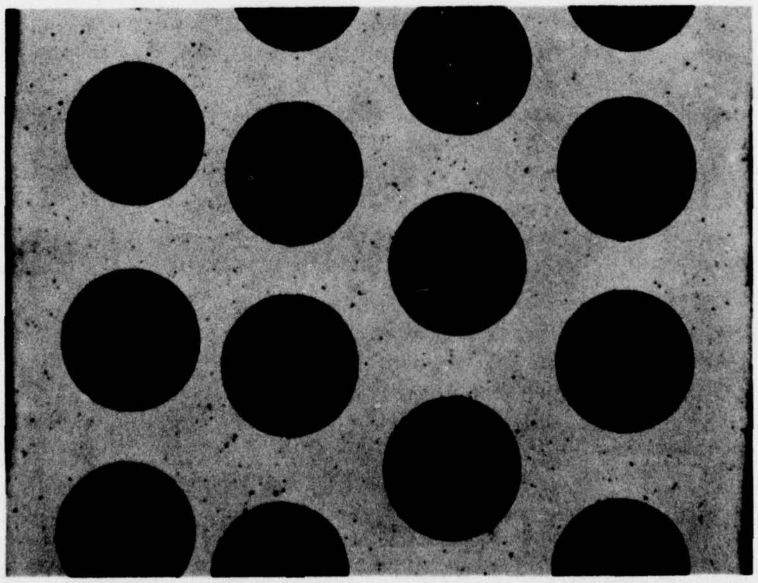


Figure 13. W-1ThO$_2$/FeCrAlY Specimens After 1000-Cycle Low Cycle Fatigue TEsts.



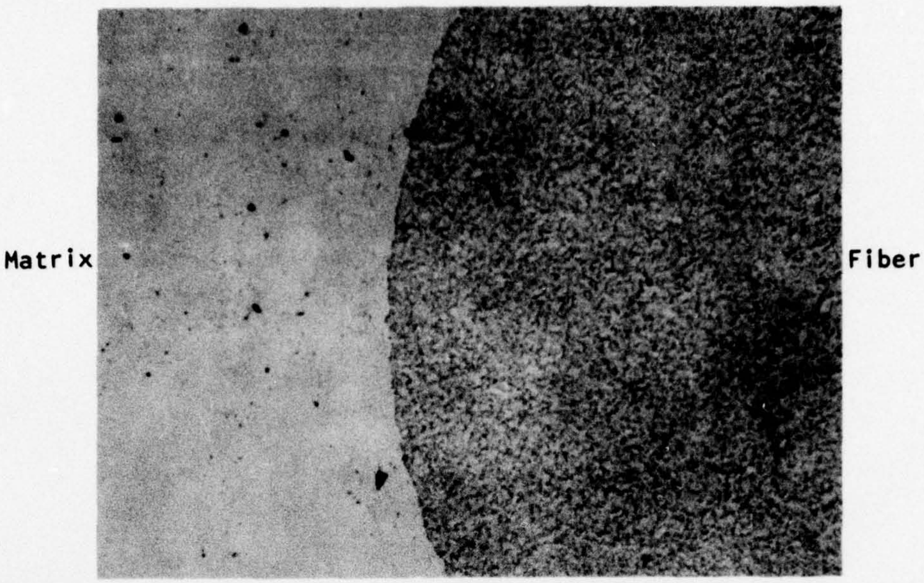
A. Hot Section

50X



B. Cool Section

Figure 14. Cross Sections Through W-1ThO$_2$/FeCrAlY Low Cycle Fatigue Specimen After 1000 Cycle Test. Note: Fiber Sections Appear Elliptical Because of ±15° Cross-Ply Fiber Orientation.



A. Hot Section

500X

B. Cool Section

Figure 15. Matrix/Fiber Interface in W/FeCrAlY LCF Specimen After Test.

Work on a current NASA contract(7) has shown that composites of 218 W/FeCrAlY with ±15°, 0° fiber distributions can withstand 1000 cycles between 427° and 1093°C (800°-2000°F) without delamination or cracking. Current investigations on the same contract are aimed at determining stress rupture properties after thermal cycling exposures in these systems. Preliminary data have indicated no long term strength degradation following such thermal cycle exposures.

3.5 Fabrication Studies

3.5.1 Monotape Fabrication

Pre-consolidated monotapes represent a potentially low cost starting material for subsequent fabrication of complex shaped parts with controlled distributions of fibers. The utility of monotapes in the fabrication of high quality airfoils (fan blades) has been demonstrated for titanium and aluminum matrix composites(8-10). Other advantages relate to ease of quality control.

Important requirements are for a fully dense product with good fiber distribution and a high quality surface for subsequent joining. Various primary fabrication parameters, surface preparation techniques and secondary fabrication (joining) parameters are being investigated in the present work.

Filament collimation and powder cloth fabrication methods have been described previously(1,2). Layers of collimated fibers were sandwiched between layers of powder cloth. By use of suitable separators (Mo foil), several experimental monotapes 1.2" x 5" were produced in one pressing. Fabrication parameters investigated were in the range 18 to 25 Ksi (124-172 M Pa) at 982°-1121°C (1800°-2050°F) for typical cycle times (time under full load) of 30 minutes. The appearance of as-fabricated W/FeCrAlY monotapes is illustrated in Figure 16. The surface grooving effects may be eliminated by substituting different reusable separator materials. A relatively rough surface may be beneficial, however, in that metal flow during the subsequent diffusion bonding cycle will facilitate good metallic bonding.

Metallographic cross sections of representative monotapes are shown in Figure 17 with fabrication temperatures and average levels of volume fraction reinforcements indicated. A consolidation pressure of about 16 Ksi (110 M Pa) for the 1093°C (2000°F) 30-minute cycle was not sufficient to produce a 100% dense monotape as shown in the top micrograph. Original powder particle boundaries were still visible and a considerable amount of microporosity was present. A pressing cycle of 25 Ksi (172 M Pa) at 1121°C (2050°F) after about 45 minutes resulted in overconsolidation with lateral fiber movement occurring and excessive flashing around the sides of the channel die. As shown in the bottom micrograph of Figure 17, a convoluted surface resulted, and it is evident that surface cleaning prior to secondary joining would tend to result in exposure of the fibers. In this particular monotape, the starting pwoder cloth thickness was less, which explains the higher volume fraction reinforcement level. The center micrograph is representative of a more acceptable monotape with sufficient excess of matrix to allow surface cleanup by mechanical abrasion or chemical etching methods. Subsequent monotape fabrication runs have been made with larger batch sizes with no significant problems of maintaining monotape quality.

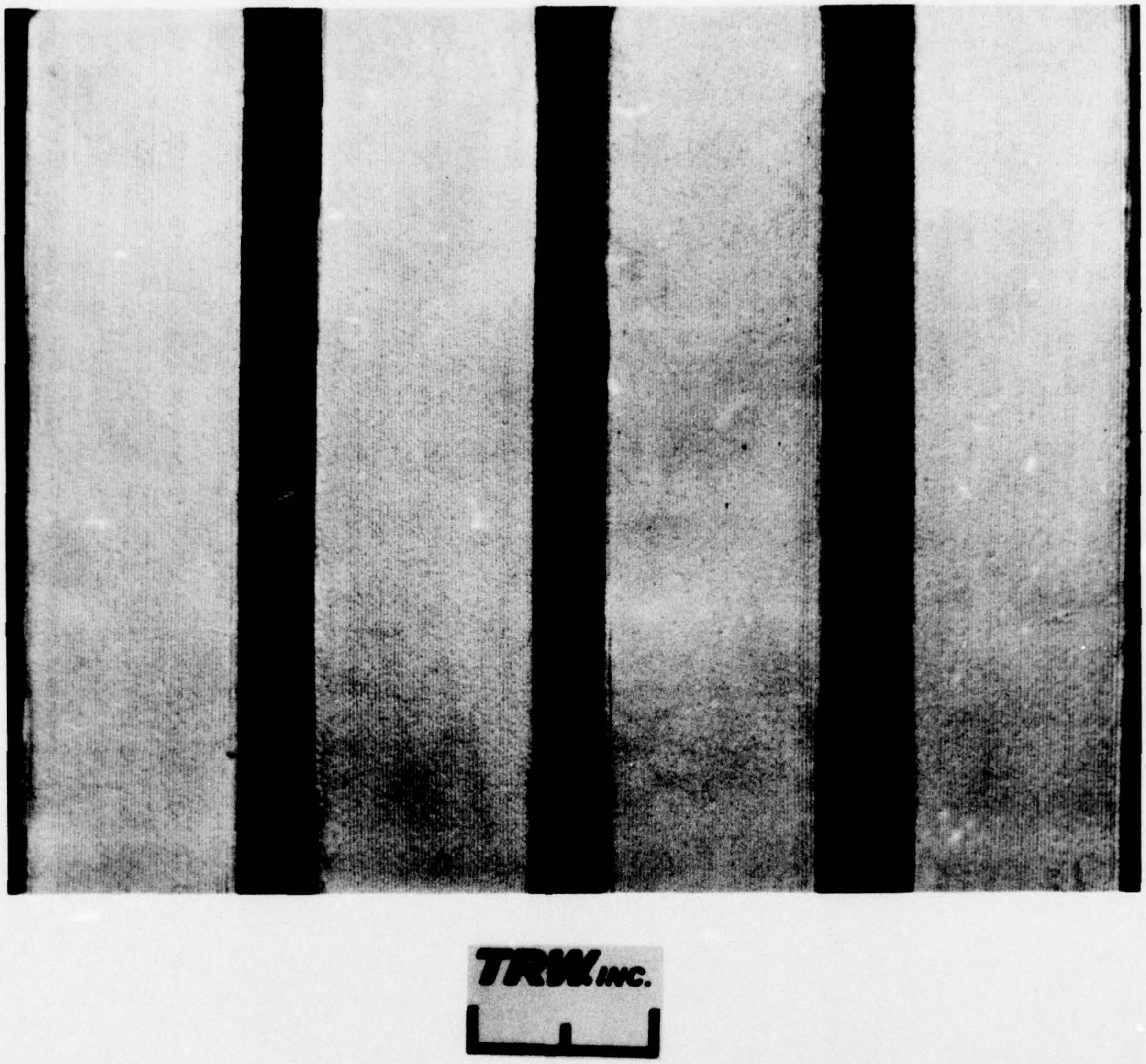


Figure 16. Appearance of As-Fabricated W/FeCrAlY Monolayer Panels.

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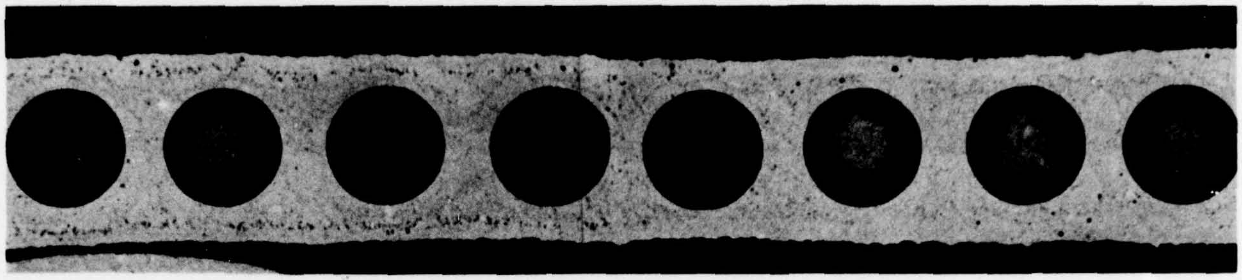
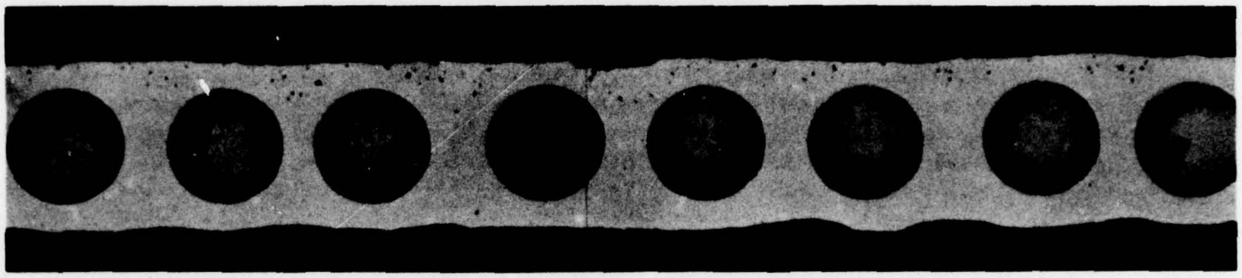
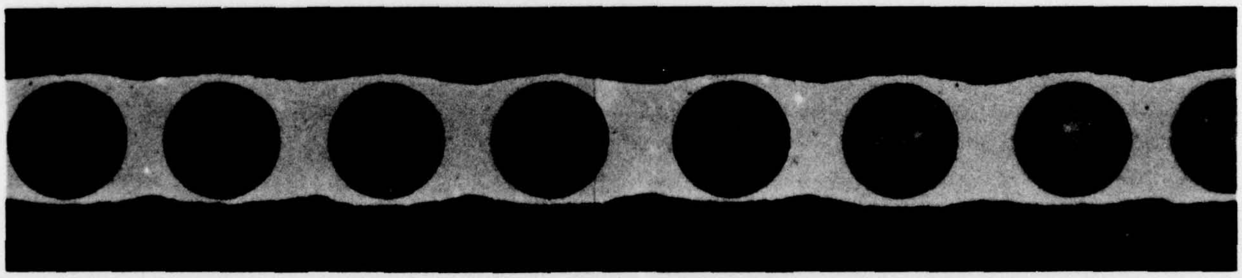


Fabricated at 1093°C - 0.327 V_f

Considerable Microporosity



Fabricated at 1121°C - 0.38 V_f



Fabricated at 1121°C - 0.48 V_f

Over Consolidated

Figure 17. Cross Sections of W-1ThO_2/FeCrAlY Monotapes. Original Magnification 50X - Reduced - 15% for Reproduction.

3.5.2 Core Leaching Studies

Some preliminary experiments to fabricate a hollow rectangular panel of W/FeCrAlY were described in a previous report(3). This panel was fabricated by the direct lay-up approach in which multiple layers of unconsolidated powder cloth and collimated fibers were consolidated in a single operation. Less precise control over filament distributions is possible by this method, compared to the two-step, pre-consolidated monotape approach, particularly in the fabrication of complex shaped parts such as airfoils. Undesirable fiber/fiber contacts can result in potential avenues of rapid oxidation in the event of blade damage. Although chemical leaching methods were successful in removing a metallic iron core, the removal rates were relatively slow unless acid concentration that slowly attacked the FeCrAlY matrix also were used. The internal cavity was bounded by an irregular metal surface and a potential problem of exposing fibers was encountered. Additional experiments, aimed at optimizing conditions for core removal by acid leaching were performed.

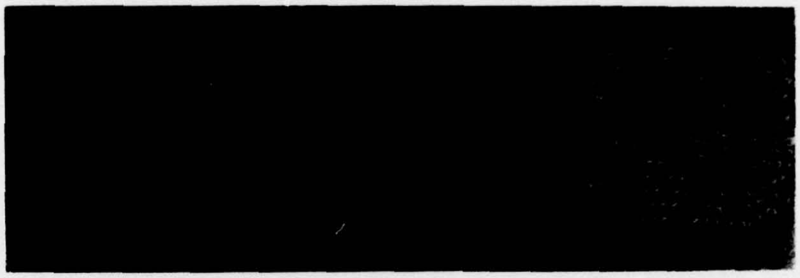
Figure 18 shows cross sections through the rectangular W/FeCrAlY panel with solid iron core before and after core removal. High leaching rates (>2 inches/hour) and very slective material dissolution were achieved by proper selection of acid concentration and etching procedure. As shown in Figure 19, a very smooth internal surface was obtained with no apparent attack of the FeCrAlY matrix. It is anticipated that more complex internal cavities could be readily produced using the same core materials and acid syphoning techniques that have been developed for hollow titanium fan blades.

3.5.3 Simulated Airfoil Fabrication

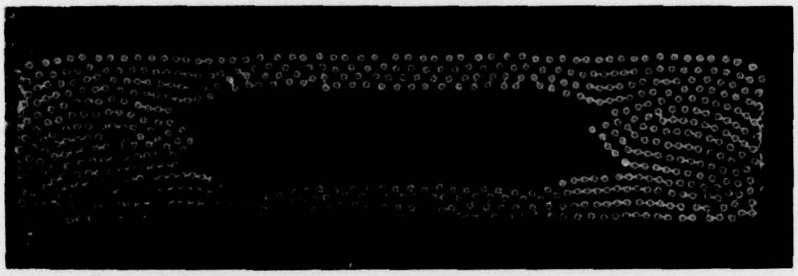
The objectives of this work were to demonstrate the feasibility of applying current composite fabrication technology to make complex shaped parts such as turbine blades and vanes. As discussed previously, pre-consolidated monotapes offer certain advantages in the fabrication of airfoils which include ease of quality control, maintenance of fiber distribution and the ability to combine different fiber orientations, volume fractions and material compositions.

Some critical experiments were designed to investigate requirements of monotape surface preparation, etc. for high quality interlaminar bonding and to demonstrate feasibility of producing hollow, airfoil shapes. There was some concern over the convoluted or ridged surface obtained on fully consolidated monotapes. Referring to Figure 17 which shows various surface conditions obtained as a function of consolidation parameters, the larger batches of monotapes had surfaces midway between the middle and bottom microphotographs in Figure 17 in terms of degree of surface corrugation.

Surface preparation techniqeus investigated included abrasion, grit blasting and chemical etching. The most successful approach as judged from the surface appearance (visually and low power microscope) and in terms of



Panel with Fe Core 4X



Core Removed by Acid Leaching 4X

Figure 18. W/FeCrAlY Hollow Composite Panel Before and After Core Removal.

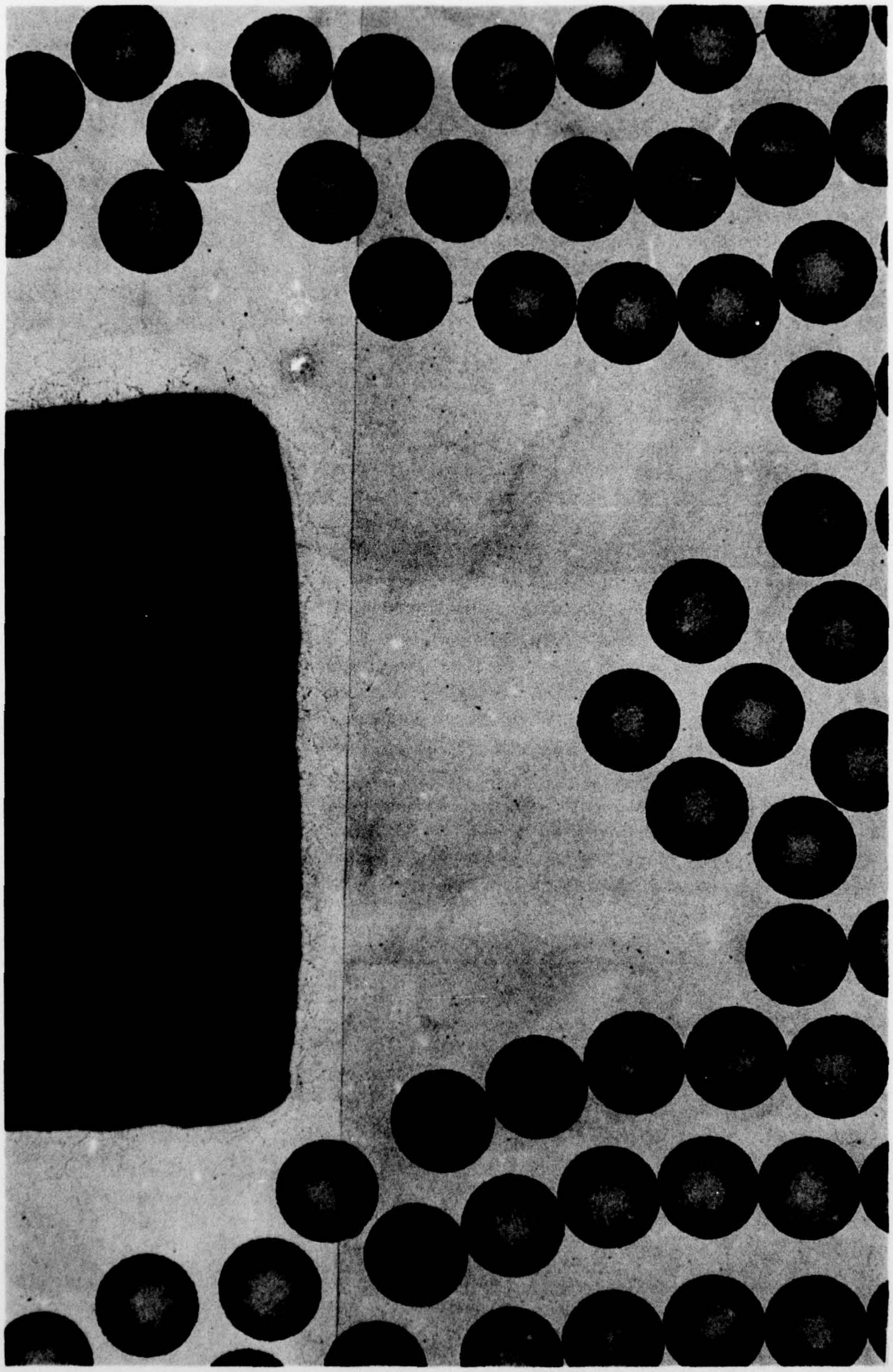


Figure 19. Cross Section Through Hollow W/FeCrAlY Panel. Note Absence of Attack on the FeCrAlY Matrix and Smooth Internal Surface.

cost effectiveness was a three-stage chemical treatment aimed at removing any surface oxides, removing the required amount of stock and smut removal.

High temperature dies for isothermal press bonding of monotapes into a suitable airfoil shape were not available. A "soft" die system was developed comprising formed sheets of TZM to provide the external airfoil contour, embedded within a relatively incompressible powder such as coarse grained Al_2O_3. Monotape plies were assembled around a leachable core with an outer cladding of FeCrAlY powder cloth. The complete assembly comprising monotape and powder cloth plies, formed TZM sheets and the inert powder pressure transmitting material was placed in a TZM channel die and hot pressed at 1093°C (2000°F) using a minimum deformation hot pressing cycle. Applied pressure was in the range 103-172 M Pa (15-25 Ksi) with the crosshead motion of the press being continuously monitored.

Figure 20 shows the appearance of the simulated vane after removal from the die and sectioning of one end. There were a maximum of 14 plies through the airfoil section and prelimination examination indicated good inter-ply bonding and excellent fiber distribution. A macro-photograph showing overall filament distribution is presented in Figure 21. The absence of fiber/fiber contacts is due to starting with pre-consolidated monolayers.

A second simulated hollow turbine blade was prepared having chord width dimensions more representative of an actual blade. Fewer plies and a larger leachable core were used. The pressing cycle was also modified to provide improved inter-ply bonding, but the same soft die procedure was used.

Figure 22 shows an overall cross section and magnified areas from convex and concave sides. The iron core was removed by leaching in acid. As shown in Figure 22, good inter-ply bonding was achieved with no trace of the original monotape surfaces. The excellent control of filament distribution in relatively thin sections, which is possible using these procedures, is demonstrated in the micrograph of the concave side. Also the relatively smooth internal surface after core removal should be noted.

These preliminary experiments therefore have indicated feasibility for fiber reinforced superalloy hollow blade fabrication using a pre-consolidated monotape approach. Extension of the leachable core approach to provide a suitable cavity for an impingement cooling tube insert with trailing edge exit slots should be readily accomplished.

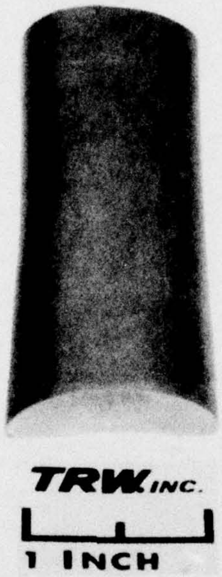
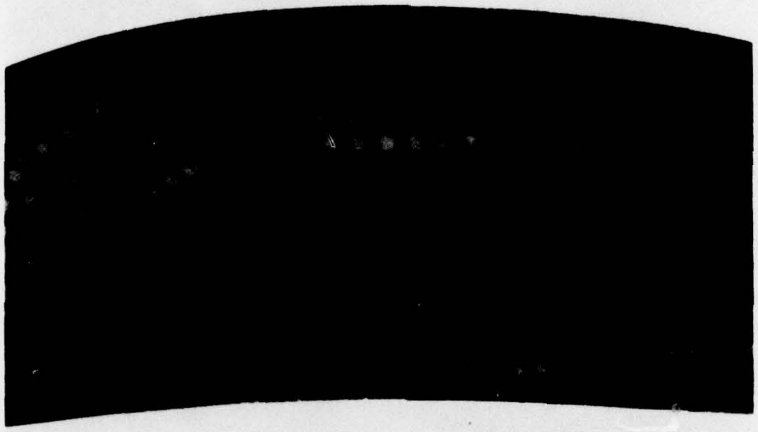


Figure 20. W/FeCrAlY Simulated Airfoil No. 1.



∼ 7X

Figure 21. Macrophotograph of Cross Section of Simulated Airfoil No. 1.

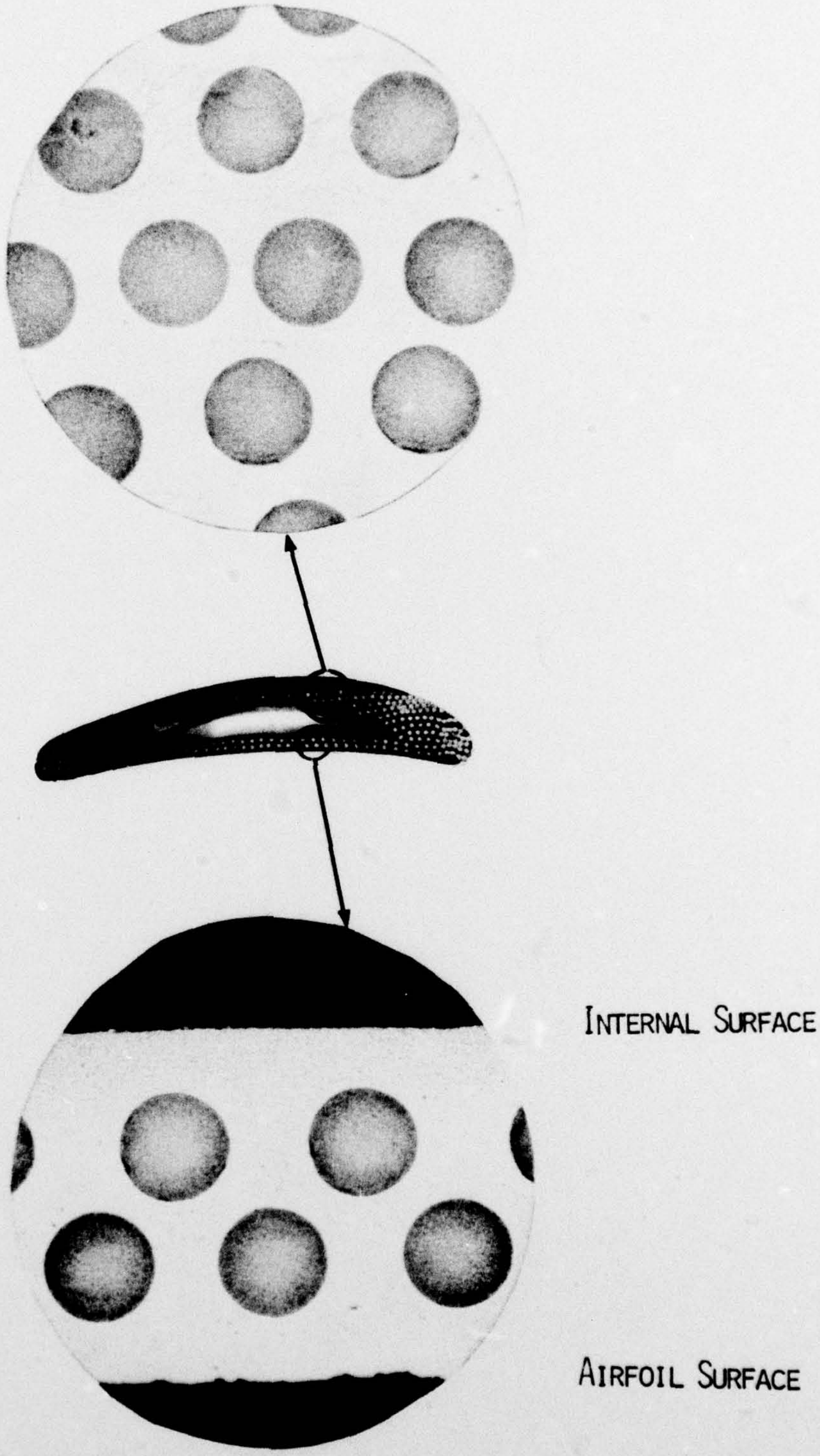


Figure 22. W/FeCrAlY Simulated Hollow Airfoil No. 2.

4.0 SUMMARY AND RECOMMENDATIONS

The objectives of this program were to continue development and characterization of W-1ThO$_2$/FeCrAlY composites which are intended for application as advanced gas turbine engine component materials. Additional property data that were developed included impact strength as a function of temperature, low cycle fatigue and thermal fatigue on angle-plied material.

Preliminary process development studies included monotape fabrication parameter determination, surface preparation, secondary diffusion bonding, leachable core studies, and simulated airfoil fabrication. The more important results of these investigations may be summarized as follows:

1. Pendulum impact tests at temperatures between ambient and 370°C (400°F) confirmed the anticipated transition from predominantly matrix controlled fracture to predominantly fiber controlled fracture with a large accompanying increase in fracture energy.

   The minimum toughness values that were obtained are above the accepted minimum requirement for turbine blade materials and at temperatures above 150°C (300°F) impact strengths in excess of 50 ft-lb are indicated.

2. Thermal cycling tests with in-phase axial loading and temperature cycles representative of blade root conditions (low cycle fatigue) indicated no structural damage in uni-axially reinforced and ±15° angle-plied specimens after 1000 cycles at cyclic stresses up to 413 M Pa (60 Ksi).

3. Thermal fatigue tests (RT-1093°C) (2000°F) on ±15° angle-plied specimens have indicated no significant problems of structural damage after 1000 cycles and therefore no significant difference in response to thermal cycling compared to the earlier tests on uniaxially reinforced specimens(2).

4. Fabrication methods were developed for producing monolayer panels (monotapes) of 0.015-inch diameter W-1ThO$_2$/FeCrAlY. Surface cleaning methods were also developed to allow successful fabrication of multi-laminate panels from monotapes.

5. The feasibility of using acid-soluble metallic cores, which can be leached away preferentially, to fabricate hollow components was demonstrated.

6. These processes were combined to fabricate simulated hollow airfoils demonstrating the feasibility of turbine blade fabrication by the pre-consolidation monotape ply process.

Recommendations for additional needed investigations are:

1. Continued development of critical physical and mechanical property data including off-axis and transverse creep behavior and long term shear strength. Physical property data that are required include thermal expansivity, thermal conductivity and elastic properties. Some of these evaluations should be performed on specimens with fiber orientations, volume fractions and fiber diameters representative of potential blade constructions.

2. Additional blade fabrication process development and blade design studies aimed at further process feasibility demonstrations for specific prototype components.

3. Manufacturing technology programs to establish cost effective processing schedules for FRS turbine components.

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