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GARRETT 21-5278-2

MATERIALS FOR ADVANCED TURBINE ENGINES

PROJECT COMPLETION REPORT
PROJECT 4

OXIDE-DISPERSION-STRENGTHENED TURBINE BLADES

VOLUME II

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SECTION I

1.0 SUMMARY

Improved performance of today's gas turbine engines is a continuing goal in the gas turbine industry. One of the driving parameters that improves performance is an increase of the turbine inlet temperature. This not only improves the thrust-to-weight ratio of an engine, but can also decrease specific fuel consumption.

One approach to solving the problems associated with higher turbine inlet temperatures is the development of materials with improved high temperature capabilities. The goals of the Materials for Advanced Turbine Engines (MATE) Project 4 were to determine the feasibility, performance, and cost of one such material, oxide dispersion strengthened (ODS) MA6000. The results of Project 4 were then compared to those obtained in MATE Project 1 (directionally solidified MAR-M 247 blades) and Project 3 (single crystal NASAIR 100 blades).

Significant program accomplishments of MATE Project 4 include the following:

- o Scale-up of the manufacturing of MA6000 material from an experimental stage to production capabilities
- o Process development for the machining of the high-pressure (HP) turbine blades from MA6000 barstock
- o 200 hours of endurance engine testing using blades machined from MA6000 in the high pressure turbine of a TFE731 turbofan engine.

Project 4 was subdivided into 10 tasks:

In Task I, the optimum processing parameters for MA6000 barstock were identified. An acceptable degree of tolerance to non-optimum processing was indicated.

Task II led to the selection of electrochemical machining (ECM) to generate the blade airfoil and shank shapes followed by conventional grinding for the platform and firtree areas.

In Task III, blade costs, including material and processing costs, were analyzed.

The mechanical, environmental, and physical properties of MA6000 were evaluated during Task IV. Mechanical property testing included tensile, creep-rupture, stress-rupture, and high-and low-cycle fatigue tests. Environmental characterization included coated and uncoated oxidation and hot-corrosion tests. Physical properties measured included density, thermal expansion, thermal conductivity, and elastic modulus.

During Task V, the blade was designed to utilize the mechanical properties of MA6000 with consideration of the required manufacturing processes.

In Task VI, a total of 126 MA6000 blades and one set of the various other components needed to test these blades were manufactured.

Task VII included three phases of component testing: bench tests, high-rotor-rig tests, and whirlpit tests.

As part of Task VIII, INCO Alloys International (formerly Wiggin Alloys Ltd, U.K.) furnished the MA6000 material for Tasks

IV and VI. Processing parameters were developed by the INCO Research and Development Center (IRDC) as part of Task I.

The Task IX engine testing was successfully completed. This testing consisted of 200 hours of engine endurance testing plus a short high temperature demonstration cycle. The testing took place in a GTEC TFE731-3B engine, with the uncooled MA6000 blades in the HP turbine. The actual engine testing took place in the following order:

- 50-hour High Cycle Fatigue (HCF) Evaluation
- 50-hour Stress Rupture Evaluation
- 50-hour Simulated Commuter Aircraft Mission
- 50-hour Low Cycle Fatigue Evaluation
- Short High Temperature Demonstration Cycle

After each test segment, the disk and blades were removed and fluorescent penetrant inspected. No detrimental signs of flaws or failure were found.

After the engine tests were finished, a posttest metallurgical inspection was conducted (Task X) which included sectioning several of the tested blades. The results of this inspection are discussed in Section IV of this report.

SECTION II

2.0 INTRODUCTION

The NASA Materials for Advanced Turbine Engines (MATE) program is a cooperative effort with industry to accelerate introduction of new materials into aircraft turbine engines. As a part of this effort, Garrett Turbine Engine Company (GTEC) was authorized under NASA Contract NAS3-20073, Project 4, to develop and demonstrate the use of ODS MA6000 machined turbine blades in advanced turbofan engines. This process development included those efforts required to transfer the technology from the previously demonstrated feasibility stage through component demonstration. Engine testing portions of the overall effort included process scale-up, alloy evaluations, mechanical property generation, hardware procurement, component testing and full scale engine testing to evaluate potential benefits.

This report constitutes Volume II of a two volume Project Completion Report presenting the results of the investigations and tests performed under Project 4. This volume covers the full scale engine testing and posttest analysis, Tasks IX and X, respectively. All other aspects of this project are covered in Volume I.

The intent of Project 4 was to develop the processing requirements to produce uncooled turbine blades machined from MA6000, and to design, test, and compare this blade to the cast, directionally solidified (DS) turbine blade used in the high-pressure turbine of the GTEC TFE731-3 turbofan engine.

Project goals associated with this program included the following:

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- Scale up and establish commercial production capability of MA6000 bar stock and the associated blade manufacturing process

- Define material properties and design a high-pressure turbine blade from this data base

- Demonstrate uncooled MA6000 blade performance through component and engine tests.

Project 4 was subdivided into the following 10 tasks:

I - Alloy process optimization
II - Blade Manufacturing Process Optimization
III - Blade Cost Analysis
IV - Material Property Characterization
V - Blade design
VI - Component Manufacture
VII - Component Testing
VIII - Subcontractor Activity
IX - Engine test
X - Posttest Analysis

Tasks I through VIII are covered in detail in Volume I of this Project Completion Report. In this document, Tasks IX and X, full scale engine test and posttest analysis, are covered in detail, including recommendations concerning the future use of ODS MA6000 in future high temperature engines.

The results of Tasks IX and X are restricted by the NASA For Early Domestic Dissemination (FEDD) policy. The FEDD legend describing the requirements of this policy is printed on the cover of this document.

SECTION III

3.0 FULL SCALE ENGINE TESTING

Scope

The objectives of the Task IX engine testing were as follows:

- Fully evaluate both the material and design of the MA6000 (ODS) turbine blades by engine testing

- Compare the performance and endurance characteristics of the MA6000 turbine blades to the directionally solidified blades tested in MATE Project 1. In addition, the MA6000 blade was compared to the single crystal blades tested in Project 3.

These objectives were first met by a back to back performance test of a TFE731-3 engine using MA6000 turbine blades in the high-pressure turbine. The results were then compared directly to the directionally solidified and single crystal turbine blades of previous MATE projects. Following this performance test came four 50-hour endurance engine tests. The tests were designed to evaluate the ability of the MA6000 turbine blades to operate in an engine environment through high cycle fatigue, stress rupture, a simulated commuter aircraft mission and low cycle fatigue testing. In addition, a high temperature demonstration cycle was also completed to evaluate the greater high temperature capabilities of MA6000. The test cycles for these test segments are shown in Figures 1, 2, 3, 4, and 5, respectively. The endurance test cycles were similar to the ones used in the MATE Projects 1 and 3 programs, so that a close comparison to the MA6000 blades was assured.

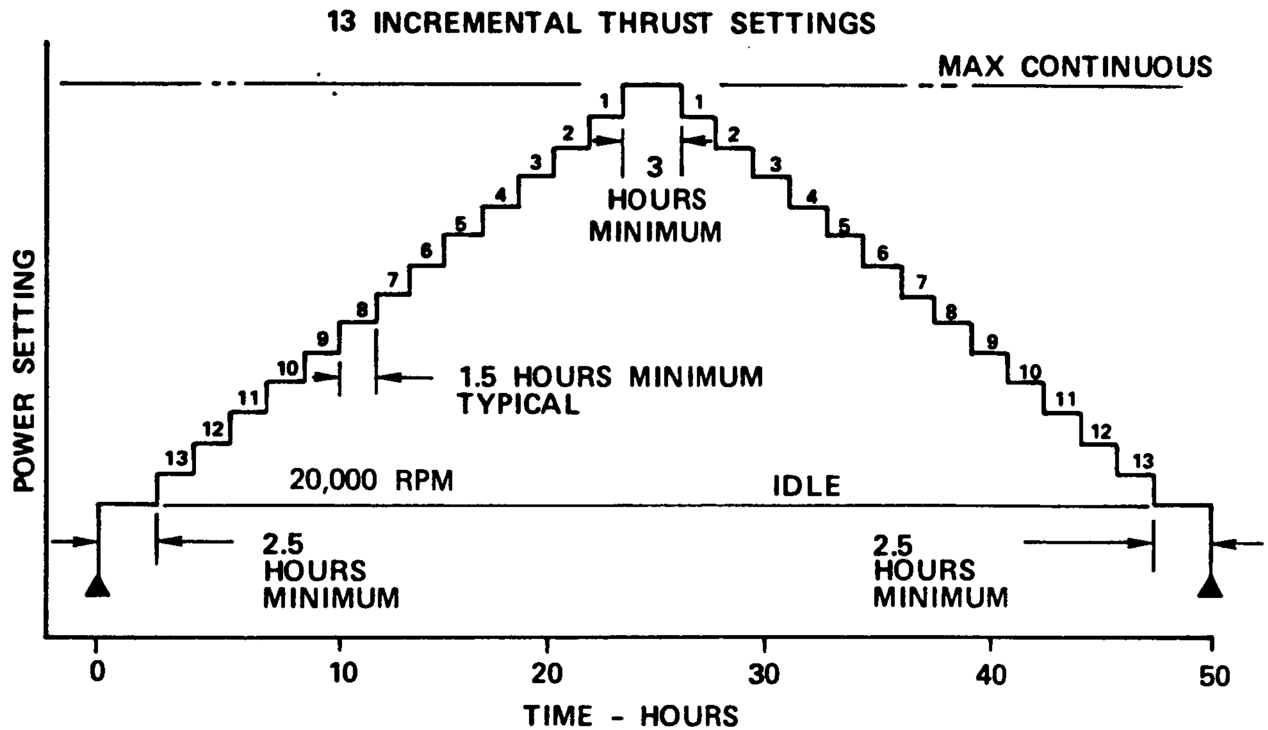

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Figure 1. First 50-Hour Test: High-Cycle-Fatigue Evaluation.

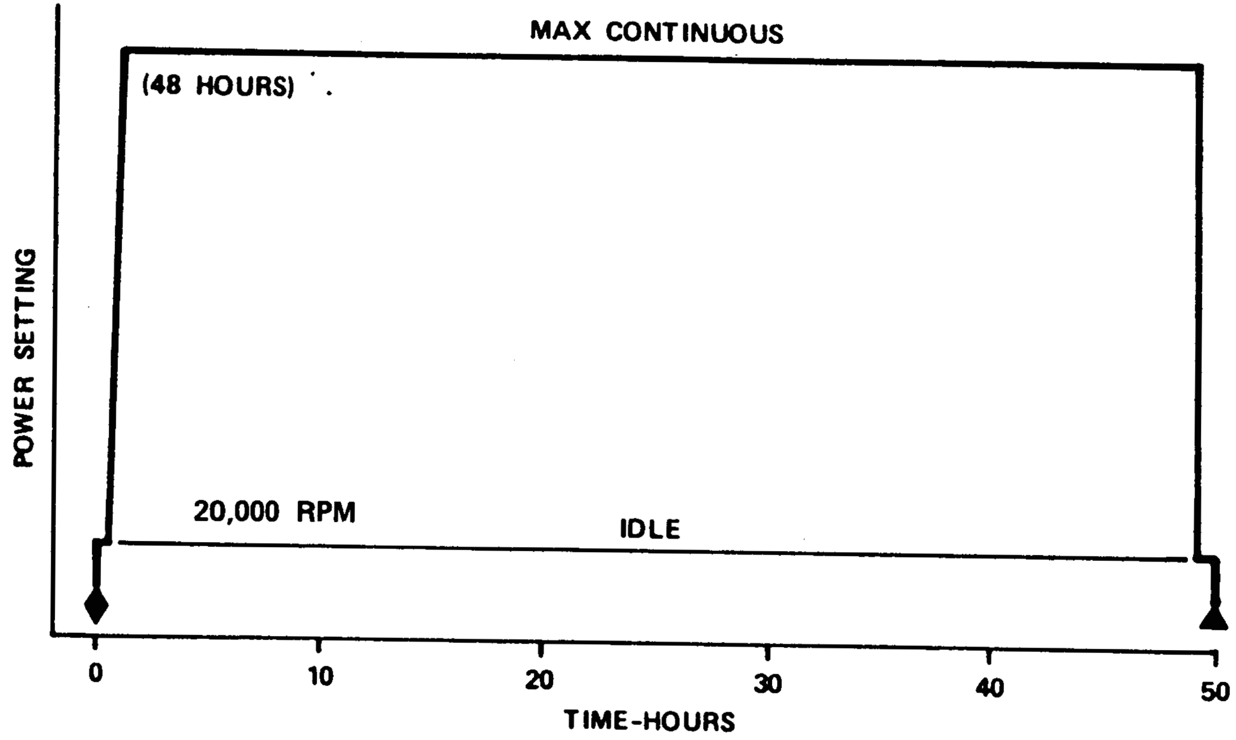

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Figure 2. Second 50-Hour Test: Stress-Rupture Evaluation.

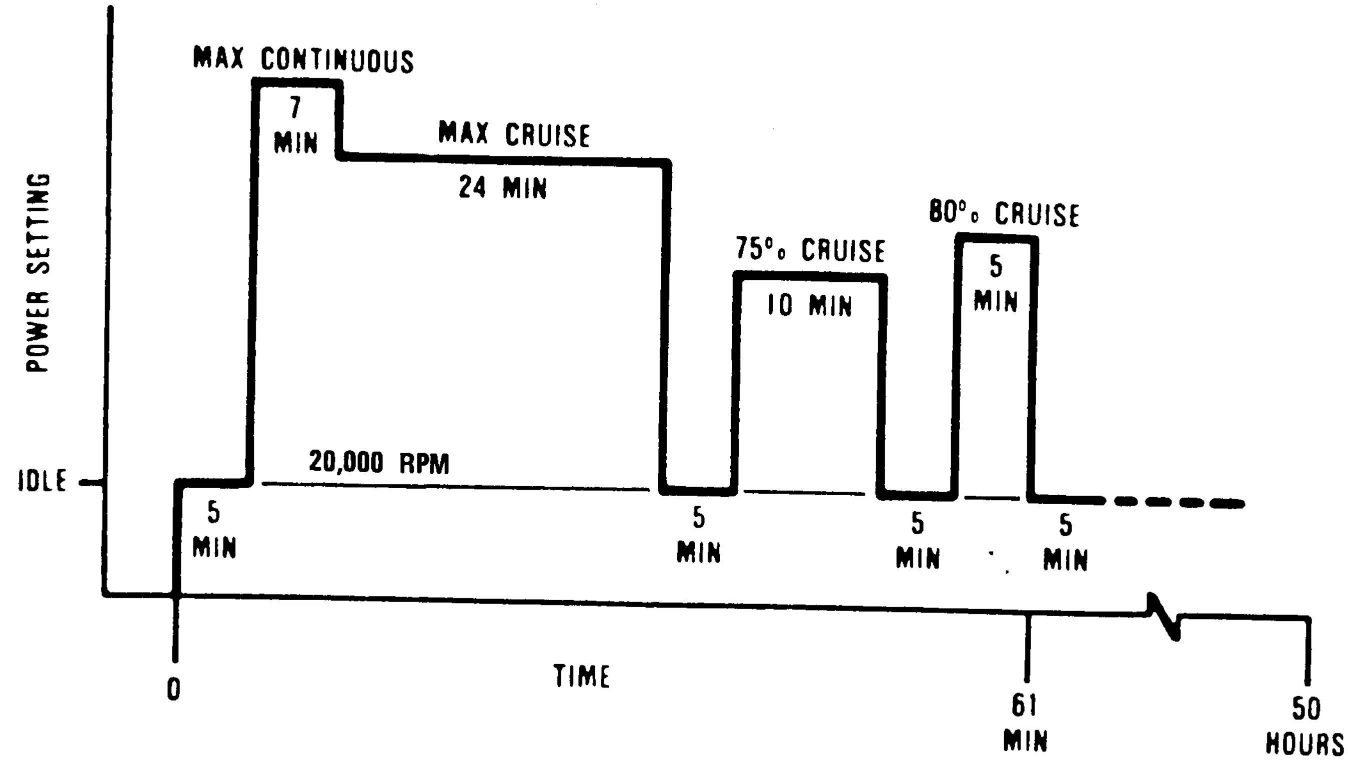

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Figure 3. Third 50-Hour Test: Simulated Commuter Aircraft Mission.

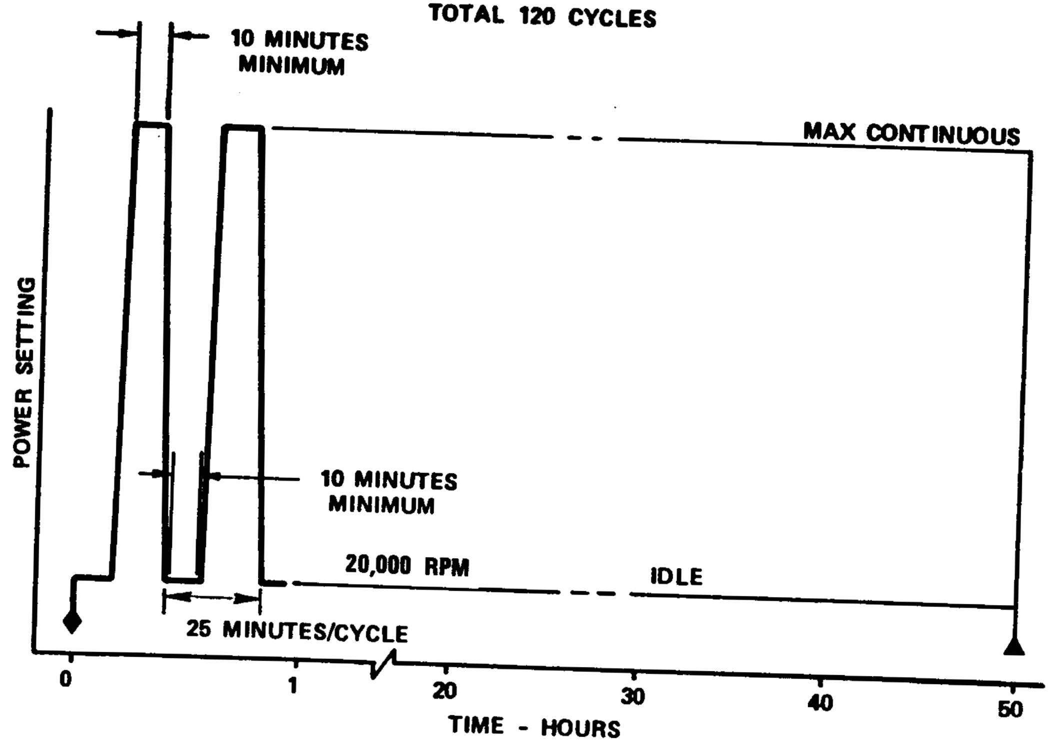

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Figure 4. Fourth 50-Hour Test: Low-Cycle-Fatigue Evaluation (Normal Accelerations and Decelerations).

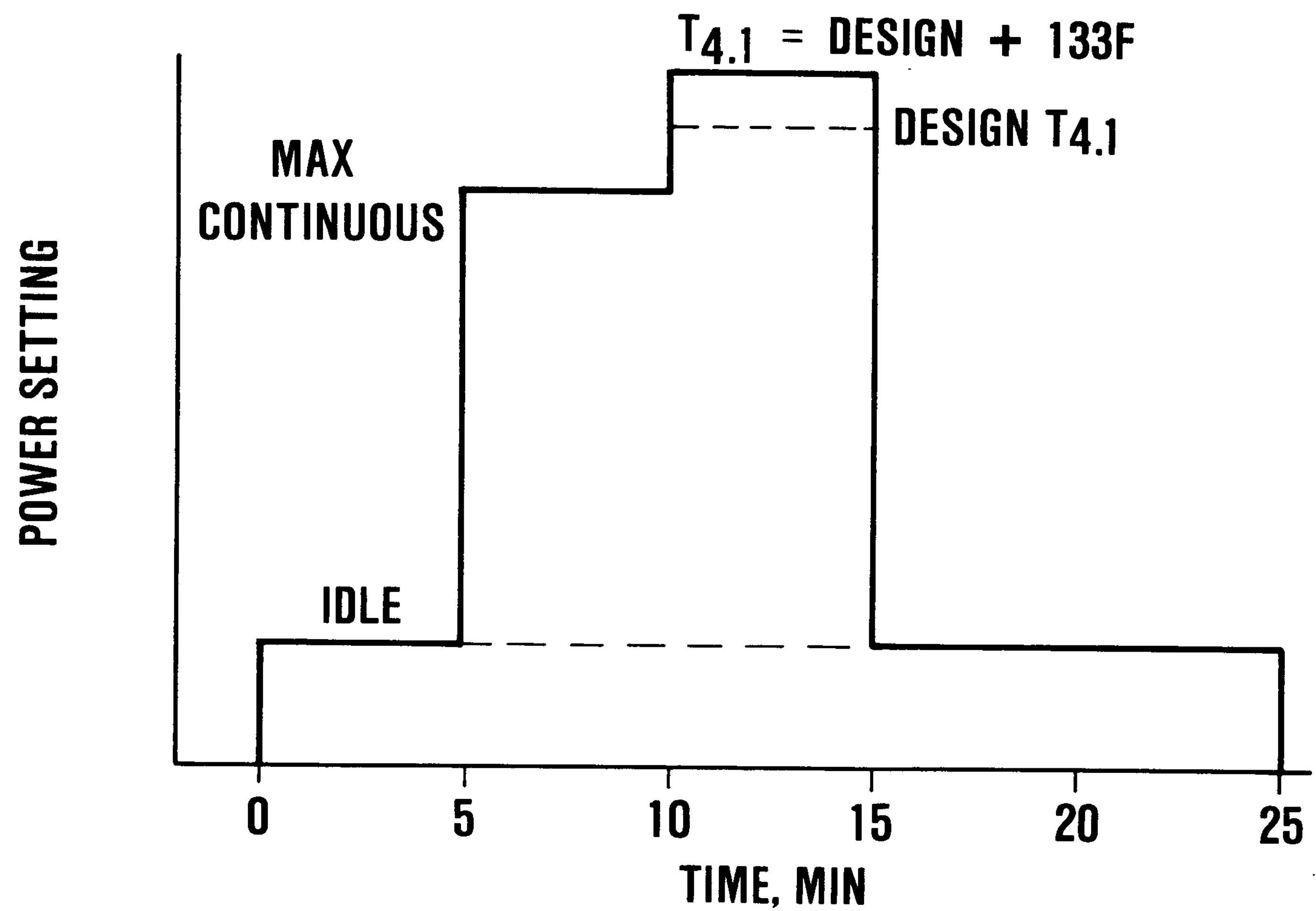

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Figure 5. High Temperature Demonstration Cycle.

Originally, it was planned that the engine test be run using two complete sets of new turbine blades machined by TRW. An extensive substitution schedule was planned to allow GTEC to evaluate the effects of each endurance cycle on the MA6000. However, due to vendor machining errors in the firtrees of these engine test blades, it was decided that the blades previously manufactured for and used in the high rotor rig component testing would be used for the engine testing. This approach presented no problems, except that the blade substitution schedule had to be reduced due to a lack of available blades. For details of the blade manufacturing problems see Volume I of the Final Report (Appendix A). The actual substitutions that took place are shown in Table 1. Even though the substitution schedule was minimal, it still allowed for both destructive and non-destructive post-test evaluation of the engine test effects on the MA6000 material.

Table 1. Blade Evaluation Schedule.

Blade S/N	Amount of Engine Time/ Engine Tests Completed
P46	150 Hours (HCF, SR, SCM)
104	150 Hours (HCF, SR, SCM)
P25	200 Hours (HCF, SR, SCM, LCF)
112	200 Hours (HCF, SR, SCM, LCF)
P22	200 Hours (HCF, SR, SCM, LCF)
122	200 Hours (HCF, SR, SCM, LCF)
101	50 Hours (LCF)
49	No Time (New blade)

3.1 Performance Testing. The MATE Project 4 MA6000 HP turbine blade is a low stress design similar to the MATE Project 1 DS blade and the Project 3 SC blade. The MATE Project 4 turbine consists of 56 blades, whereas the Project 1 HP turbine consisted of 62 blades. This blade count reduction was due to the lower stress constraints placed on the MA6000. In addition, the MATE Project 4 blade is 8 percent thicker axially than the Project 1 blade in the firtree region. For design details, see Volume I of this report. Engine hardware modifications that were necessary to adapt the MA6000 blades to the TFE731-3B engine are listed below:

Part Name:

MATE HP Blades - MA6000
HP Turbine Disk
HP Shroud Segments
HP Nozzle
First Stage LP Nozzle
HP Platform Seal.

Two performance tests were run. After the first performance test, a small shroud rub was observed. At that point, all the blades specified for engine testing had their tips ground 15-18 mils. The disk was reassembled, and a second performance test took place. No further difficulties were encountered.

3.2 Endurance Testing. Endurance testing was accomplished in four 50-hour test segments. After each test segment, the engine was disassembled and inspected. In addition, inspections also took place at the mid-point of the high cycle fatigue and stress rupture tests as a safety precaution. The HP blades and disk were inspected, both visually and by fluorescent-penetrant-inspection (FPI), for cracking and any other signs of distress.

All endurance testing was done with standard engine monitoring instrumentation at GTEC's "Site B" facility in Torrance, California, as shown in Figure 6.

The first 50-hour test cycle was used to verify the MATE Project 4 blade vibratory response and evaluate the resistance of the blades to high cycle fatigue (Figure 1). This test was accomplished as scheduled. No operating problems occurred, and all test parameters were within limits. Mid and posttest inspection revealed no distress on any of the MA6000 blades or support hardware. After inspection and photo-documentation, the disk was rebalanced and the engine was reassembled for the second 50-hour endurance test.

The second 50-hour test called for a stress rupture evaluation (Figure 2). No problems arose during testing. However, upon disassembling the engines, a small shroud rub was found, as shown in Figure 7. There was no significant damage to the turbine blade tips; therefore, dressing of the tips was deemed unnecessary. Upon inspection of the shroud, it was found that the rub occurred due to a high spot, which was subsequently machined off per TFE731-3B specifications. Subsequent FPI and visual inspection performed when the engine was disassembled at the midpoint and end of test segments indicated no difficulties or signs of distress.

After the wheel was photo-documented and rebalanced, the engine was reassembled for the third 50-hour test, a simulated commuter mission (Figure 3). No problems were encountered during this test. Upon posttest visual analysis, however, it was noted that almost all blades had fretting on their firtrees, accompanied by minor pitting. This was photo-documented, and two of the blades with the worst fretting were submitted for metallurgical inspection. Results of inspection are discussed in Section

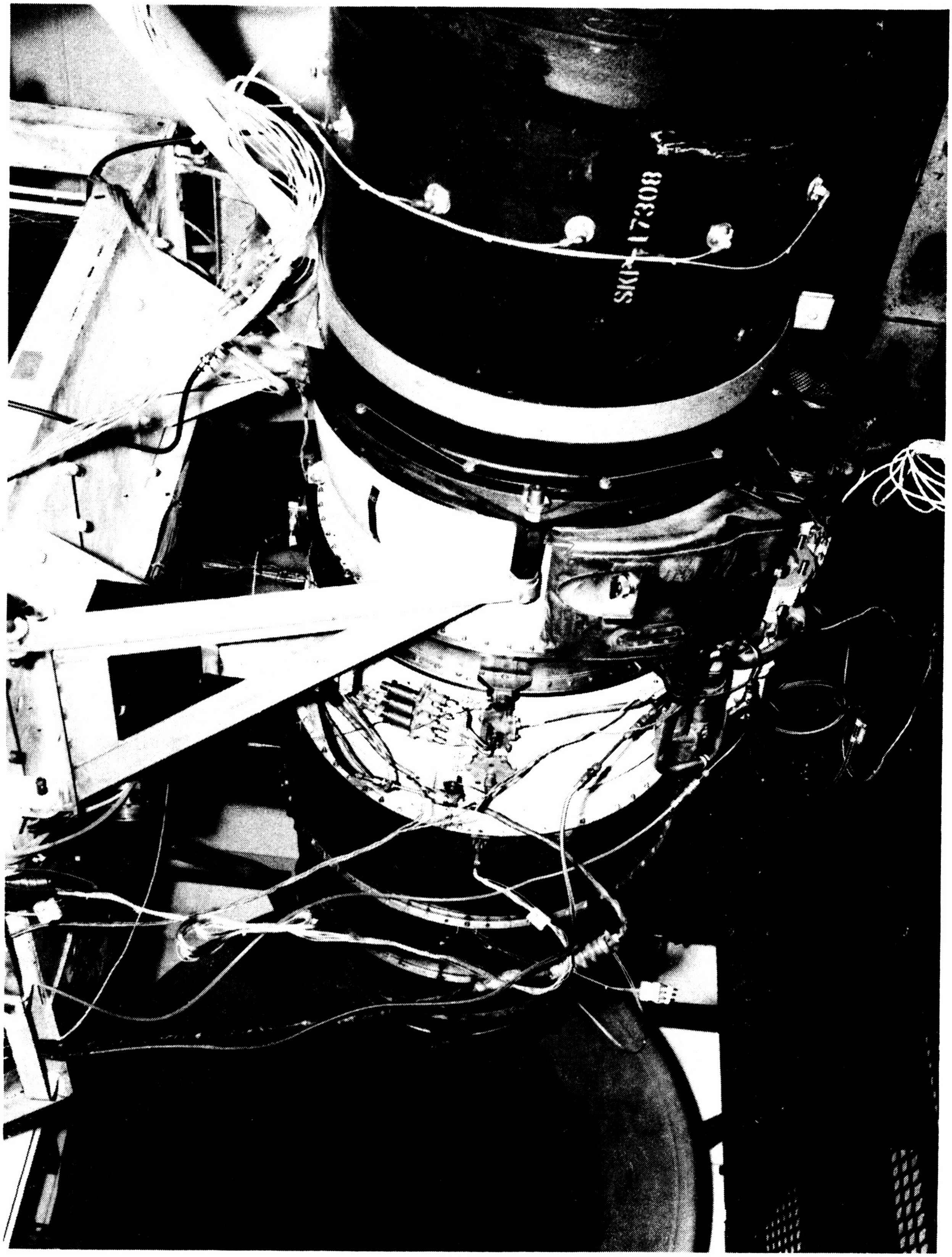

Figure 6. TFE731 Installed in Torrance Test Cell.

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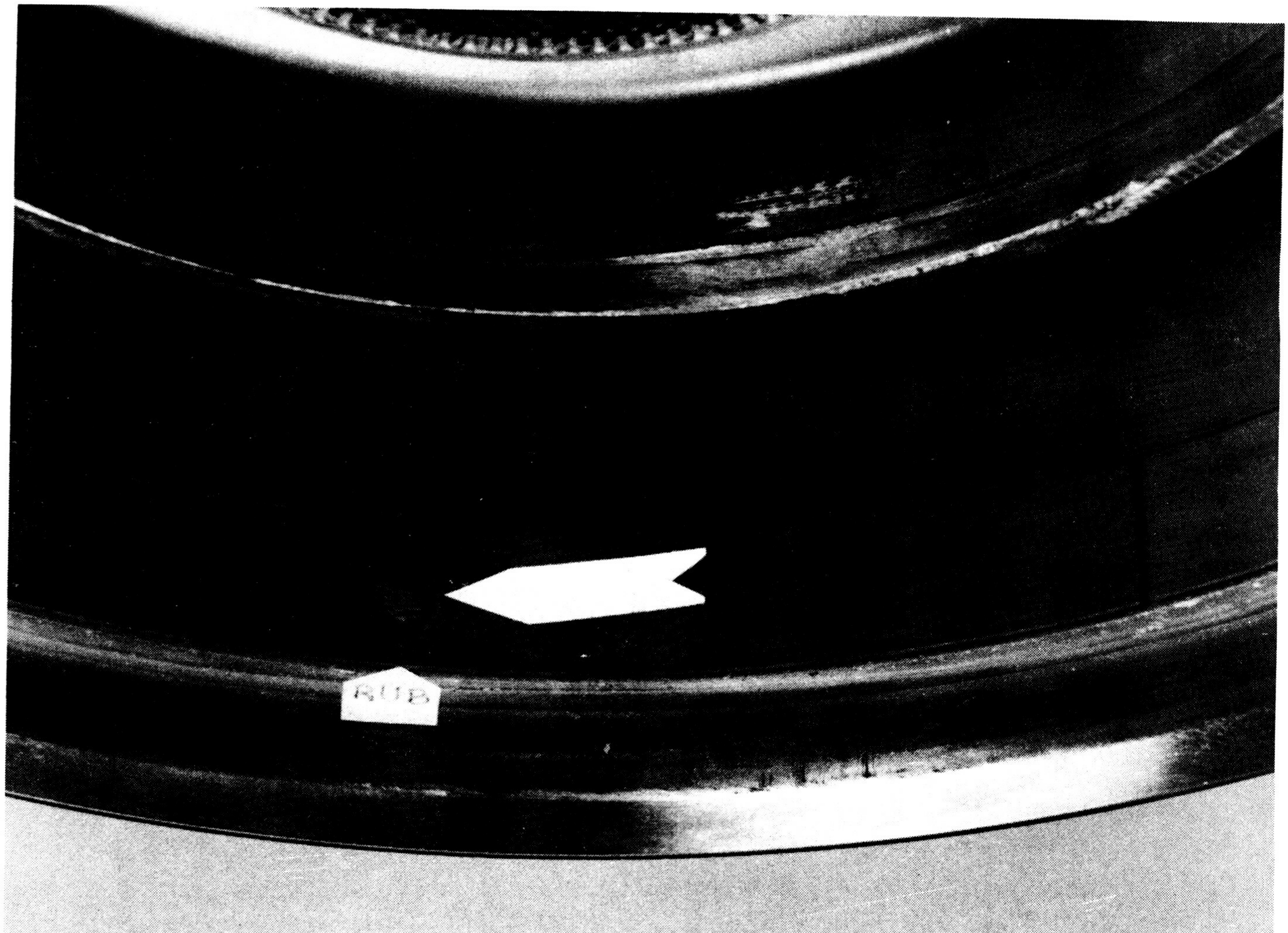

Figure 7. Small Shroud Rub.

4.2.2. These blades were replaced with extra blades from the high rotor rig previously unused in the engine test to determine when the fretting began.

The wheel was rebalanced and the engine reassembled for the final 50-hour test, low cycle fatigue evaluation (Figure 4). Normal accelerations and decelerations were maintained for all cycles. No problems were encountered during this testing. At the end of testing, the engine was shipped back to Phoenix for teardown and inspection. The two replacement blades with 50 hours of engine time were pulled and one of them was submitted for metallurgical inspection. A blade with the full 200 hours of engine time was also submitted for metallurgical inspection. This was done to compare the blade airfoil plus the firtree fretting and pitting after 50, 150 and 200 hours of engine time. The results of the metallurgical inspection of the blades is discussed in the posttest analysis of this report (Section 4.2.2). Five blades were substituted at this point, in preparation for the high temperature demonstration cycle. Three of these five blades were among the mismachined lot from TRW.

The final test was a high temperature demonstration cycle, and was designed to expose the MA6000 blades to a T_4 approximately 133F greater than that normally experienced in a TFE731-3B. This increase in temperature was accomplished by installing a reduced area nozzle that back pressured the low pressure spool, thus allowing a greater fuel flow without overspeeding the engine. The high temperature was maintained for five minutes. The disk and blades after the high temperature demonstration cycle are shown in Figure 8. The engine was then disassembled and visual inspections of the HP blades and disk revealed no degradation. The blades and disk were then cleaned and penetrant inspected. Again, no flaws or signs of distress were found.

Figure 8. Disk and Blades After High-Temperature Demonstration Cycle.

SECTION IV

4.0 POSTTEST EVALUATION

This section discusses the results of the visual, nondestructive (NDE) and metallurgical evaluations of the MA6000 turbine blades during and following the 200-hour endurance engine test.

The endurance test, conducted in a TFE731-3B turbofan engine, consisted of four 50-hour cycles listed below. A two-hour engine performance run was made prior to the 200-hour test, plus a short high-temperature demonstration was run after the 200-hour test. Details of these engine test cycles have been discussed previously in this report.

- Performance calibration: 2 hours
- High cycle fatigue simulation: 50 hours
- Stress rupture cycle test: 50 hours
- Commuter aircraft operational cycle: 50 hours
- Low cycle fatigue simulation: 50 hours
- High temperature demonstration cycle: 5 minutes

4.1 **Visual and NDE Evaluation**. Following each 50-hour run, the turbine rotor was disassembled for detailed inspection of the blades and disk. The MA6000 turbine blades and the Waspalloy disk were visually examined under low power optical magnification (7X-10X) and inspected using Fluorescent Penetrant Inspection (FPI) techniques.

After the first 50-hour cycle [high-cycle fatigue (HCF) simulation run], no signs of distress on either the blades or disk were observed.

A minor blade tip rub occurred during the stress rupture cycle test (between 50 and 100 hours), due to a high spot on the shroud. The blade tips are shown in Figure 9. The rub was primarily localized inboard of the leading edge and less than 0.100 inches wide. It was not considered severe enough to require dressing the blade tips. The shroud was cleaned, however, prior to continuation of the test to avoid another rub. No further rubs were experienced for the duration of the engine testing. No blades were found to have rejectable FPI indications after this second test.

At the end of the simulated commuter aircraft cycle (150 total hours), surface oxidation was noted on the airfoil surfaces. This was manifested as thin scales, discoloration and oxidation pits that were barely visible to the unaided eye.

Firtree fretting was also noticed at this time. Although it had not been noted earlier, it was considered likely that the fretting started earlier in the engine testing. Therefore, prior to running the last 50-hour cycle (low-cycle fatigue simulation), two blades were replaced with new, as-machined spares to provide comparative evaluation of the firtree fretting.

Following the successful completion of the scheduled engine testing, a general assessment of the rotor's condition was made. Overall, the blades and disk survived the 200-hour engine test in excellent condition. The minor airfoil surface oxidation and discoloration was compared to the cast single crystal (SC) NASAIR 100 bladed rotor (Project 3) after a 200-hour engine test run (Figure 10), and the two sets of blades were found to be similar in appearance.

The rotor was subsequently disassembled for detailed inspection. Visual examination showed that the surface oxidation condition did not worsen in terms of scaling and oxidation pits

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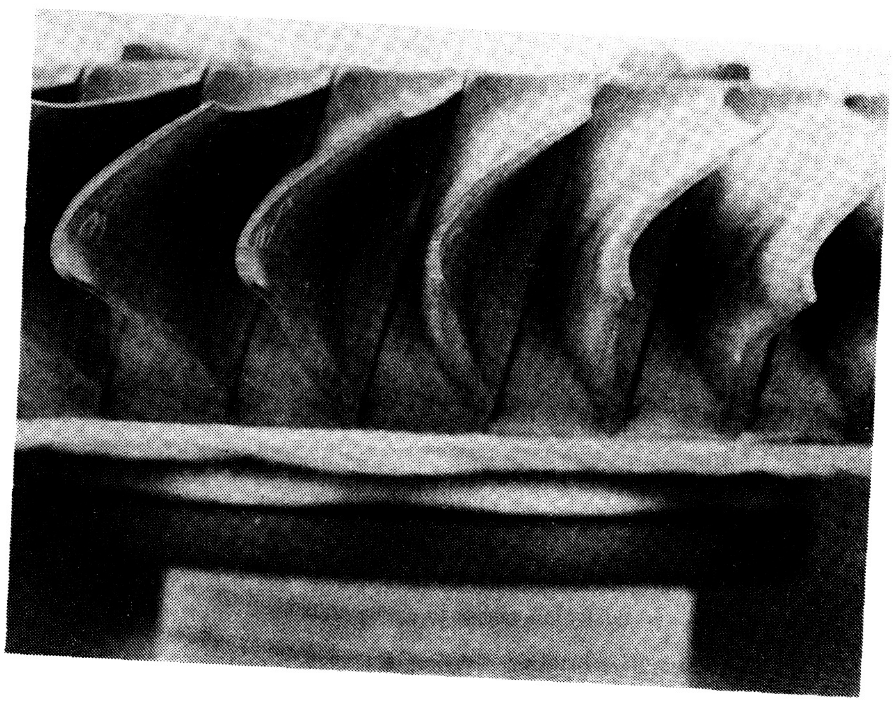
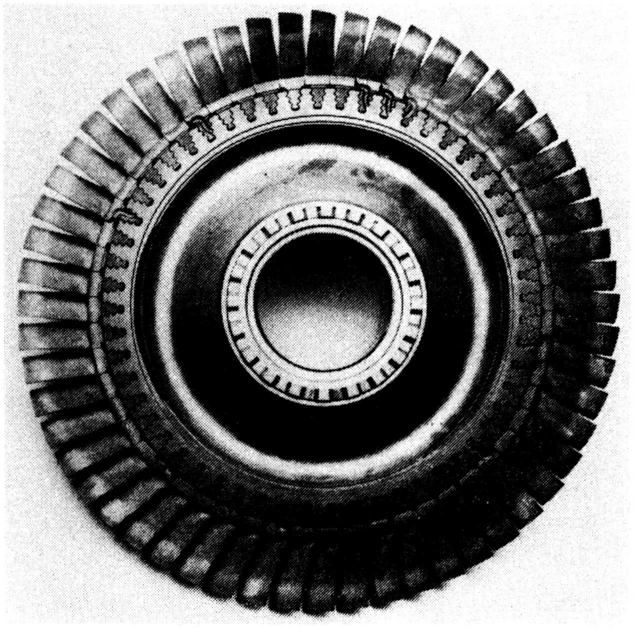
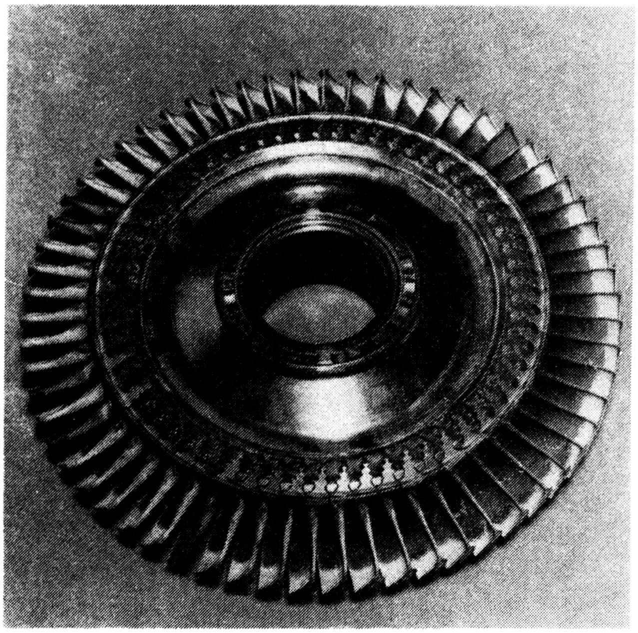


Figure 9. Tip Rub on MA6000 Turbine Blades During Stress Rupture Cycle Test.



MA6000



SC NASAIR 100

Figure 10. MA6000 Turbine Rotor Compared to Single-Crystal NASAIR 100 After 200-Hour Endurance Engine Test.

as compared to the previous cycles. Firtree fretting was observed on the blade after only 50 hours verifying the assumption that the fretting initiated prior to the 150-hour test when it was first noticed. The 200-hour blades showed only a slight worsening of the fretting condition, particularly at the contact surface of the lowest firtree lobe. None of the blades or the disk were rejected after visual examination and FPI.

4.2 Metallurgical Evaluation. Metallographical sectioning of representative MA6000 turbine blades following the completion of the testing is shown in Figure 11. To provide a baseline comparison, an unexposed blade was similarly sectioned and studied. Results of the examination focusing on macro- and microstructural morphology, firtree fretting, and blade oxidation condition are discussed in detail below.

4.2.1 Macro- and Microstructure. The typical macrostructure of the blades revealed highly textured directionally recrystallized grains characteristic of MA6000, as shown in the photomicrographs in Figure 12. The regions between large grains were inhabited by small high aspect ratio grains, also characteristic of the recrystallized alloy.

Optical photomicrographs of the microstructure of MA6000 comparing an unexposed blade to a 200-hour endurance engine tested blade are shown in Figure 13. Under light optics, both blades show a fine gamma prime morphology.

Scanning Electron Microscopy (SEM) of the unexposed blade revealed a cuboidal gamma prime phase structure in a background of very fine gamma matrix. Coarsening of the gamma prime precipitates was observed in the thermally exposed blade (Figures 14

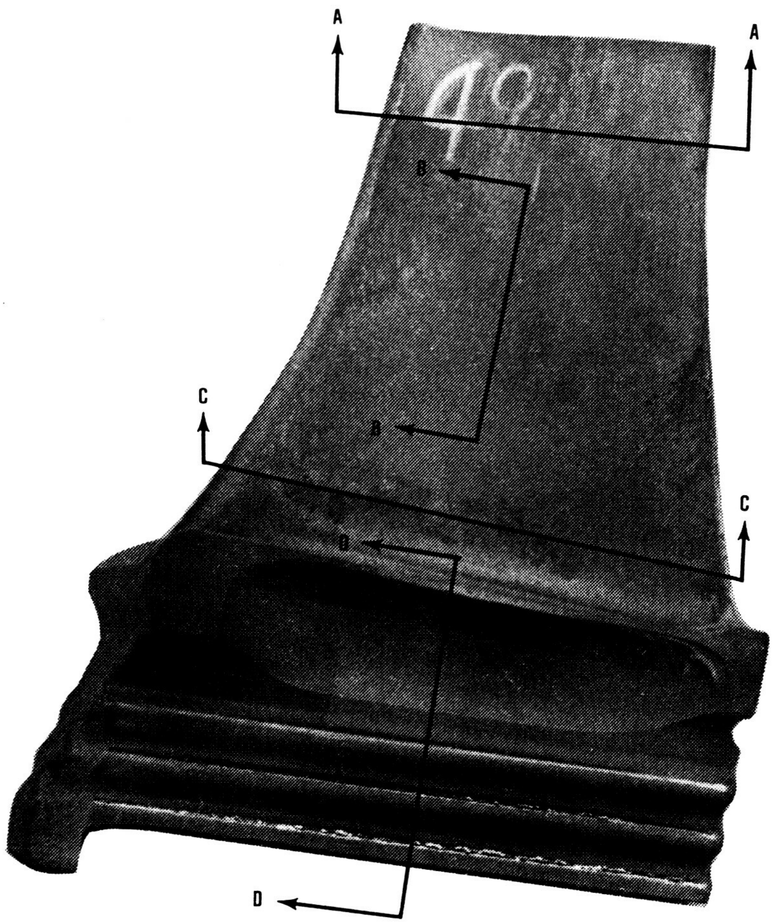


Figure 11. Metallurgical Sectioning Scheme of MA6000 Blade.

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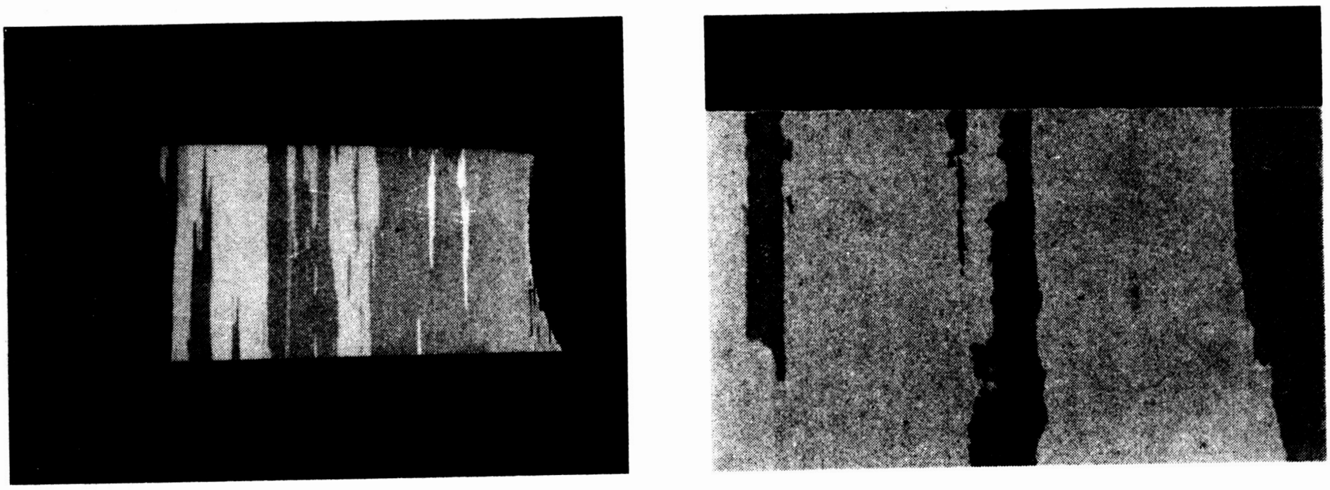
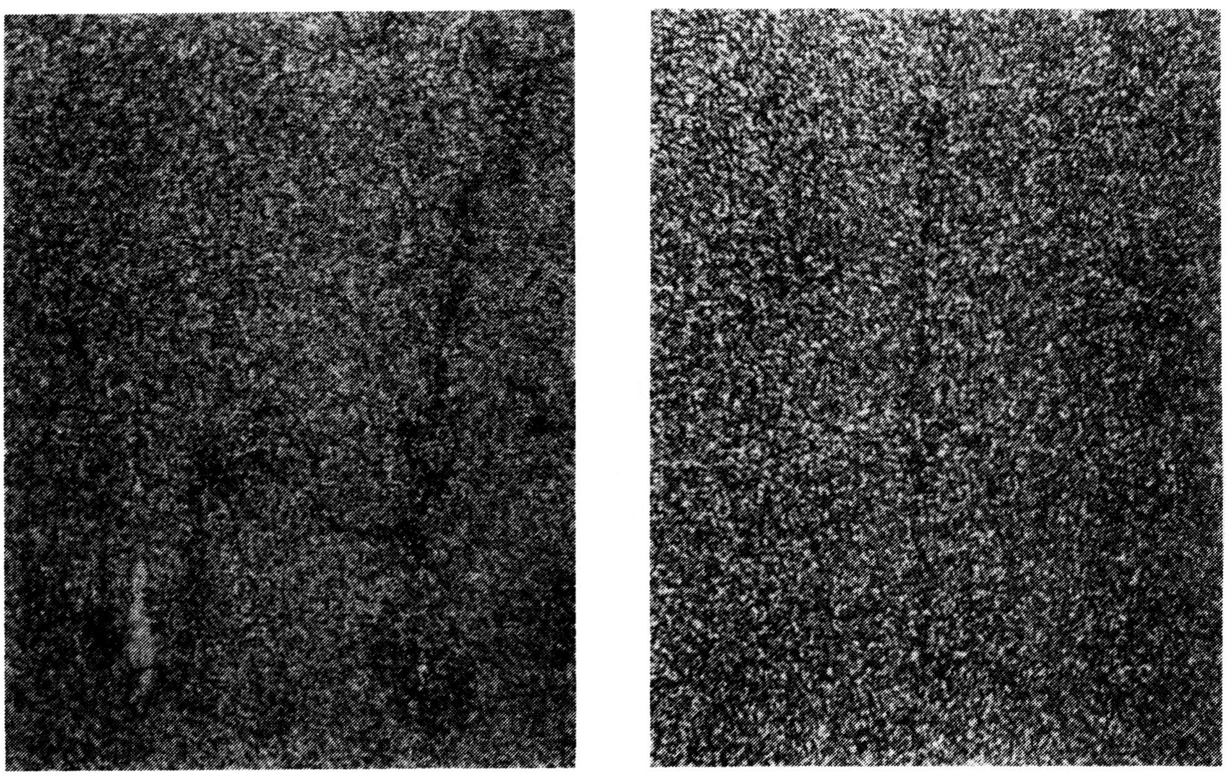


7x 70x

Figure 12. Typical Macrostructure of MA6000 Blade Used in 200-Hour Endurance Engine Test.



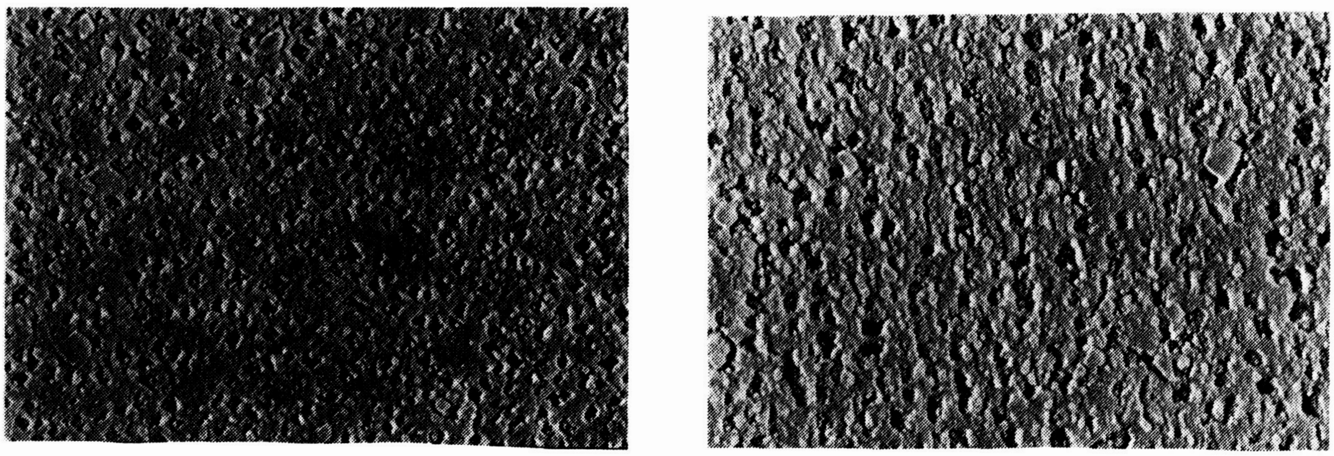
UNEXPOSED BLADE

200-HOUR BLADE

MAGNIFICATION: 1000x

(SECTION A-A)

Figure 13. Optical Micrograph of MA6000 Blade Before and After 200-Hour Endurance Engine Test Showing Typical Gamma Prime Morphology.



UNEXPOSED BLADE

200-HOUR BLADE

MAGNIFICATION: 10,000x

(SECTION A-A)

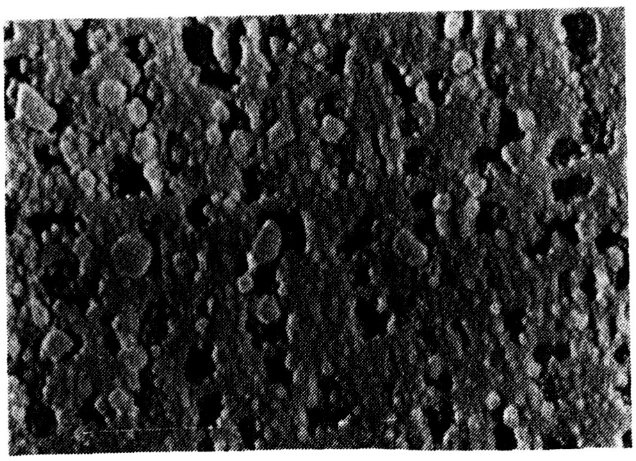
Figure 14. Scanning Electron Micrographs of MA6000 Turbine Blade Before and After 200-Hour Test Comparing Gamma Prime Size.

and 15). As discussed in Volume I, Section 4.2.1 of this report, this coarsening accounts for the decrease in tensile and rupture strength of the alloy between the temperatures of 1300 and 1800F. Beyond these temperature regimes, the high temperature properties of the alloy becomes primarily controlled by the oxide dispersion.

4.2.2 Firtree Fretting. The fretting condition at the firtree region of a 50- and 200-hour blade are compared in Figure 16. Since the condition of the 150-hour blade was similar to the 200-hour blade, the latter blade was used in this evaluation to represent the maximum exposure condition observed. Initiation of fretting at the contact surfaces of the firtree lobes after 50 hours was observed on one blade. The 200-hour blades showed that the fretting worsened at the bottom lobe but not at the upper two lobes. Under microexamination of the firtree cross-section shown in Figure 17, the fretted surface appeared as a very shallow, cold, worked metal, no more than 0.0005 inches deep. Under microexamination, there was very little difference seen in the depth and severity of fretting between the 50-hour blade (Figure 18) and the 200-hour blade (Figure 19).

4.2.3 Blade Oxidation. The surface oxidation was generally uniform and approximately 0.0008 inches thick (Figure 20). However, a more severe grain boundary type of oxidation was observed in the blade microsections. This intergranular oxidation (IGO) condition appears to be more severe where the grain boundary intercepts the free surface at a relatively steep angle. Thus, at the airfoil tip and platform outboard surfaces (Figure 21), and likewise at the firtree lobe areas (Figure 22), IGO extends as deep as 0.0015 inches after 50 hours and propagates to depths of 0.0025 after 200 hours. The airfoil IGO, in comparison, was measured to be an average of 0.0010 inches after 200 hours of engine running.

UNEXPOSED BLADE



200-HOUR BLADE

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Figure 15. SEM Micrographs of MA6000 Turbine Blade Before and After 200-Hour Test Comparing Gamma Prime Morphology.

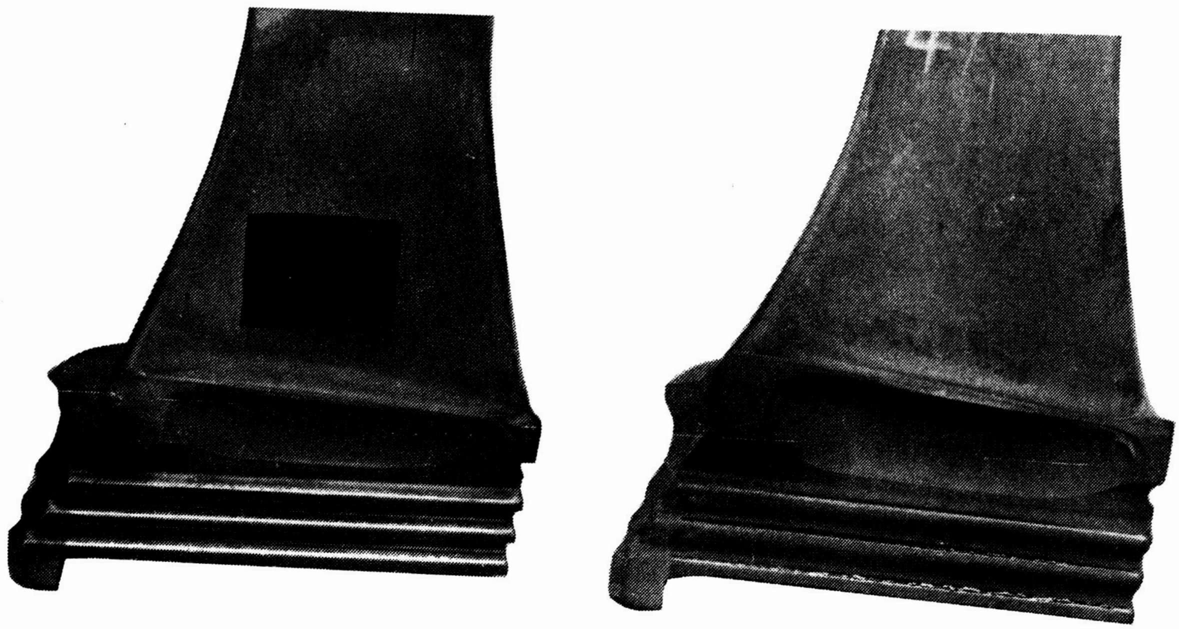

Figure 16. Firtree Fretting After 50 Hours (Left) and 200 Hours (Right).

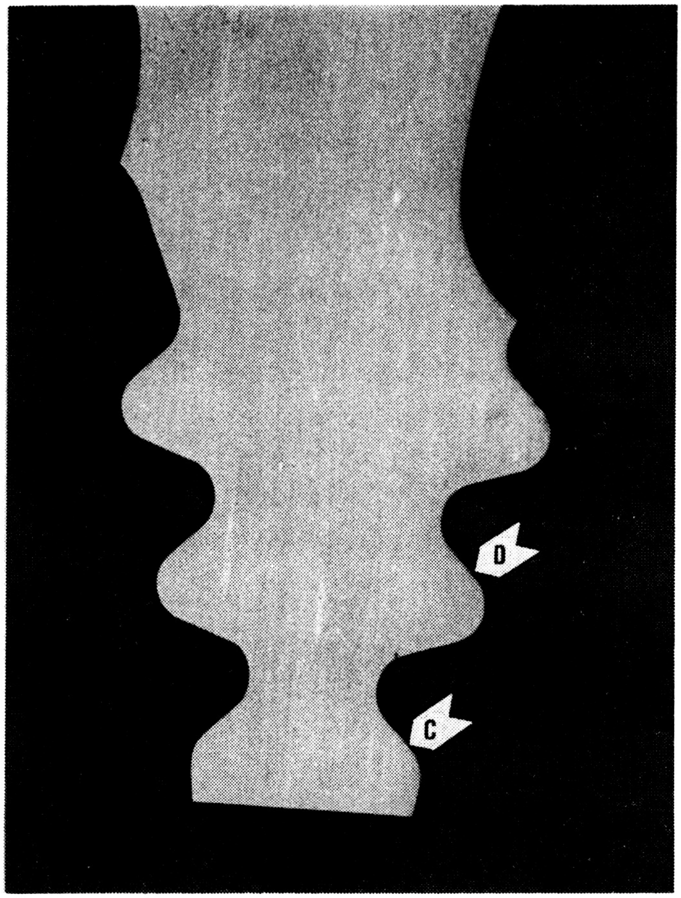

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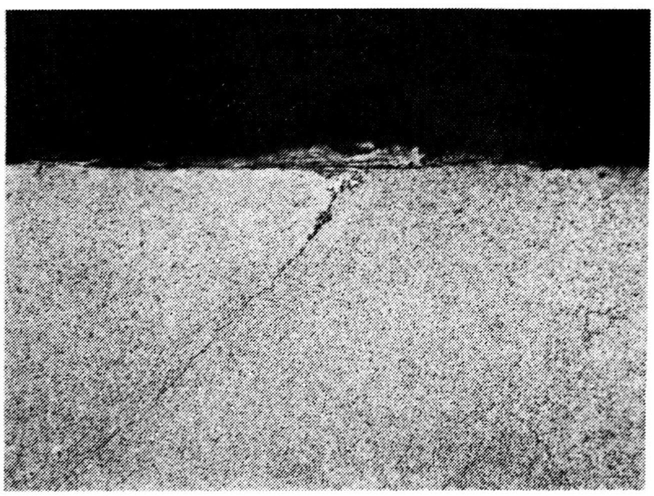
Figure 17. Firtree Cross-Section to Evaluate Fretting Condition.



LOBE SECTION C

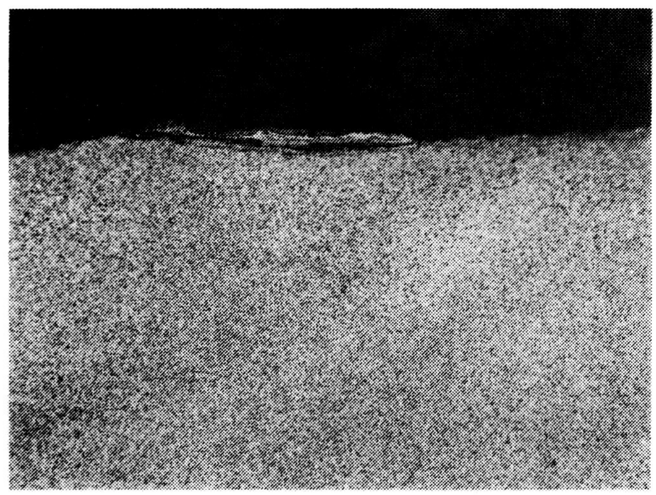


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Figure 18. Firtree Fretting of MA6000 Blade After 50-Hour Engine Test.

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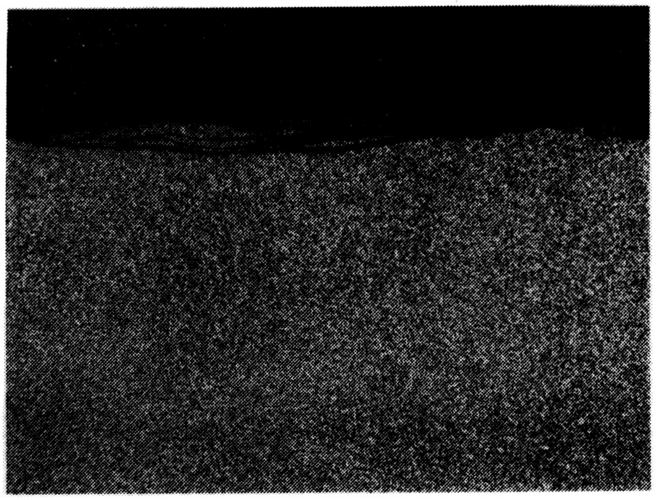

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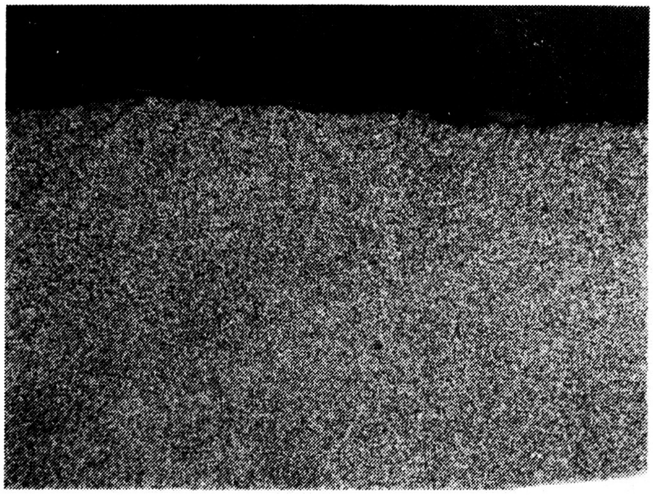

LOBE SECTION D

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Figure 19. Firtree Fretting of MA6000 Blade After 200-Hour Engine Test.

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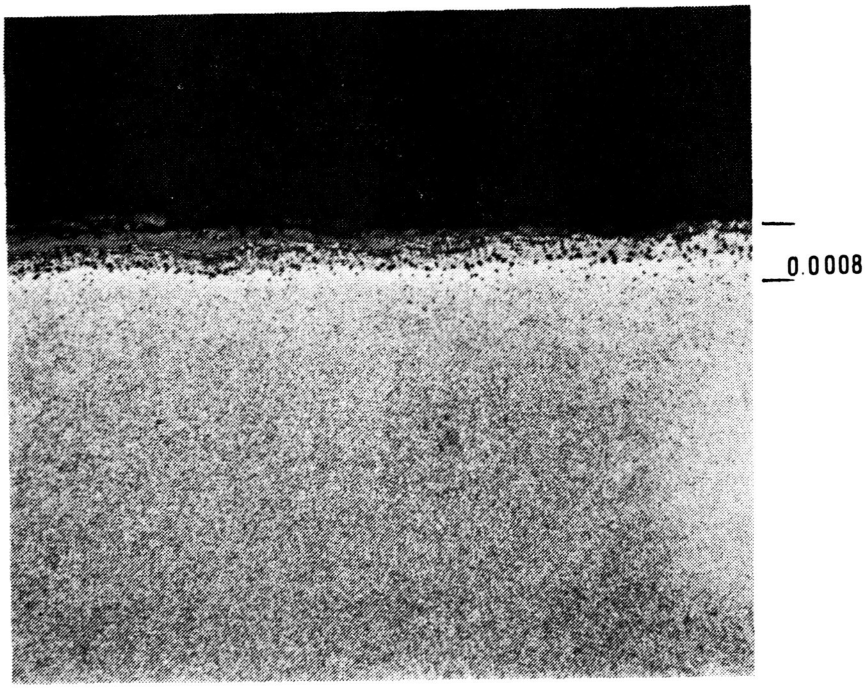

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Figure 20. Surface Oxidation in MA6000 Turbine Blade After 200-Hour Endurance Engine Test.

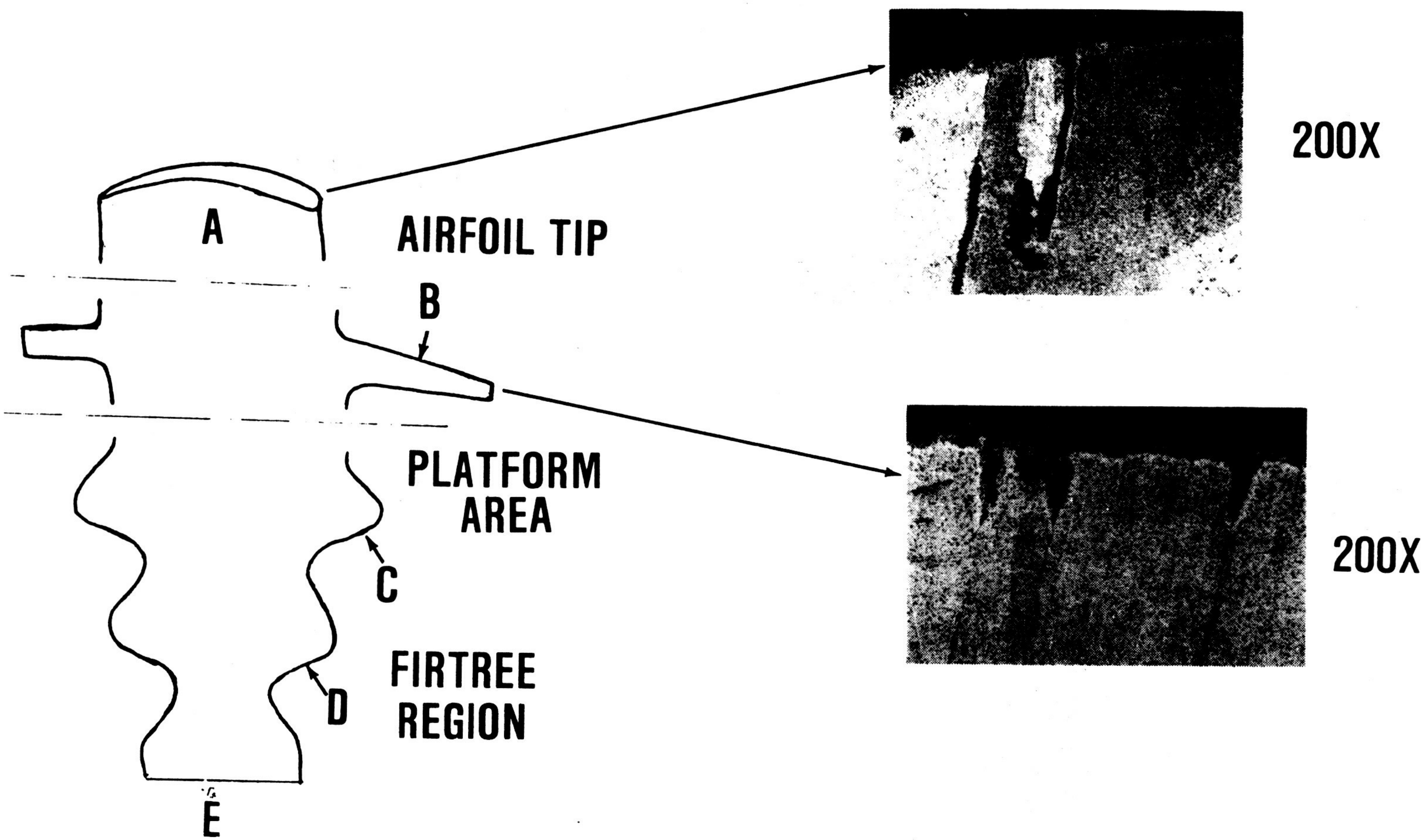

Figure 21. Grain Boundary Oxidation in MA6000 Turbine Blade After 200-Hour Endurance Engine Test.

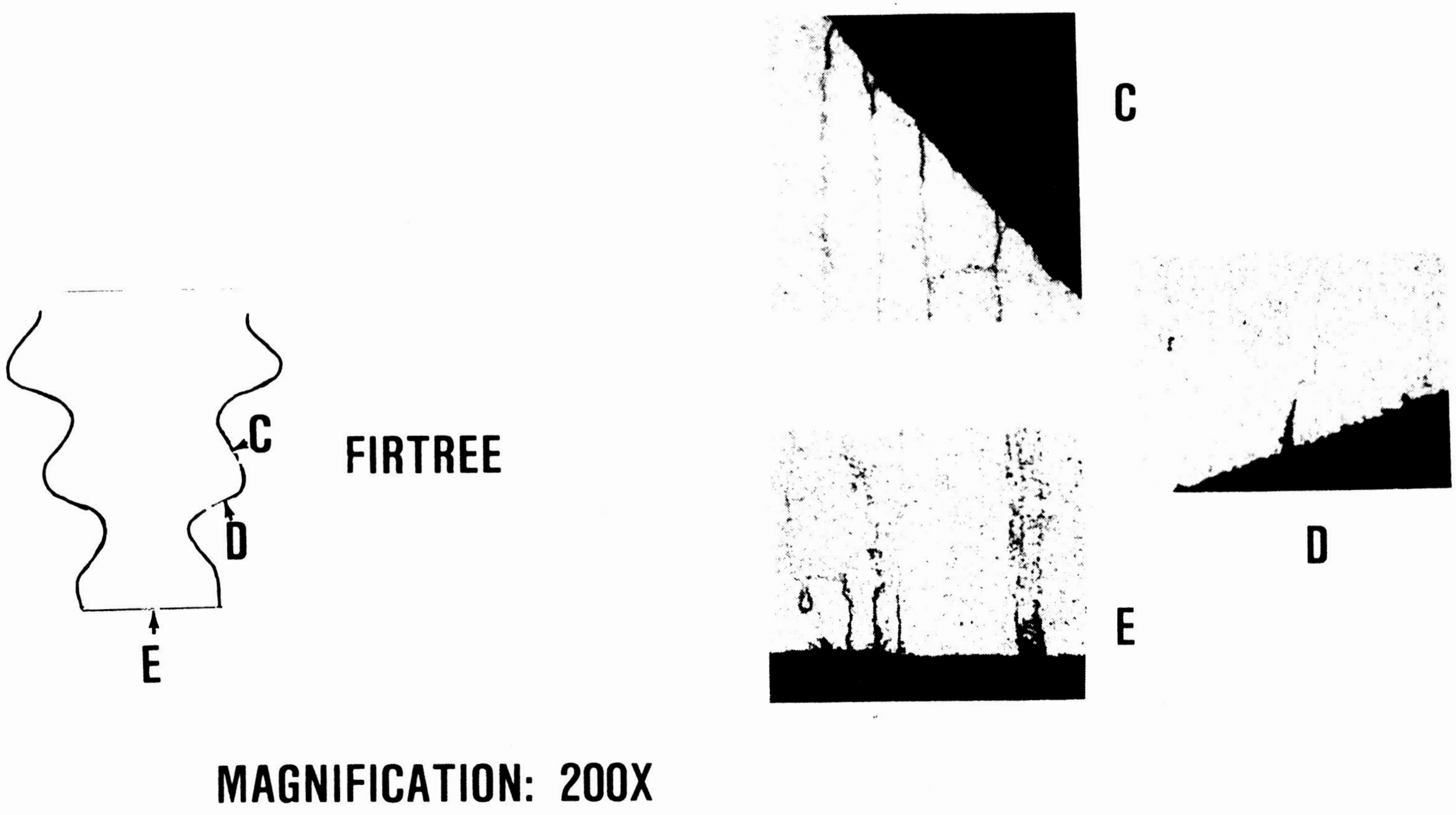

Figure 22. Grain Boundary Oxidation at the Firtree Region of MA6000 Turbine Blade After 200-Hour Endurance Engine Test.

SEM photomicrographs of typical IGO are shown in Figure 23. Energy Dispersive X-ray analysis (EDAX) comparing the matrix (Figure 24) and the oxidation region (Figure 25) shows a higher level of chromium in the latter. This suggests chromium oxide as the predominant oxidation product in the alloy system. An EDAX scan of the area adjacent to the oxidized region did not reveal any significant elemental depletion. It has been reported by M.J. Fleetwood (J. Inst. Metals 1966, Vol. 94, p.218) that Cr diffusion is enhanced in thoriated alloys such as those prepared by attrition milling of fine powders. His study indicated that this rapid diffusion was attributed to a very high density of dislocations and subgrain boundaries in dispersion strengthened alloys which might then result in the absence of a well-defined depleted zone, at least one that is not readily observed from the relatively qualitative peaks of an EDAX analysis.

The intergranular oxidation observed in these turbine blades tends to confirm that MA6000 is not as oxidation resistant as MAR-M 247 alloy. As noted earlier in this program, MA6000 alloy will require oxidation protection such as NiCrAlY coatings if it is to survive a long term engine operating environment.

The oxidation attack on the firtree region may be alleviated by the application of sputtered MAR-M 247 alloy coating. MAR-M 247 has demonstrated superior oxidation resistance over MA6000.

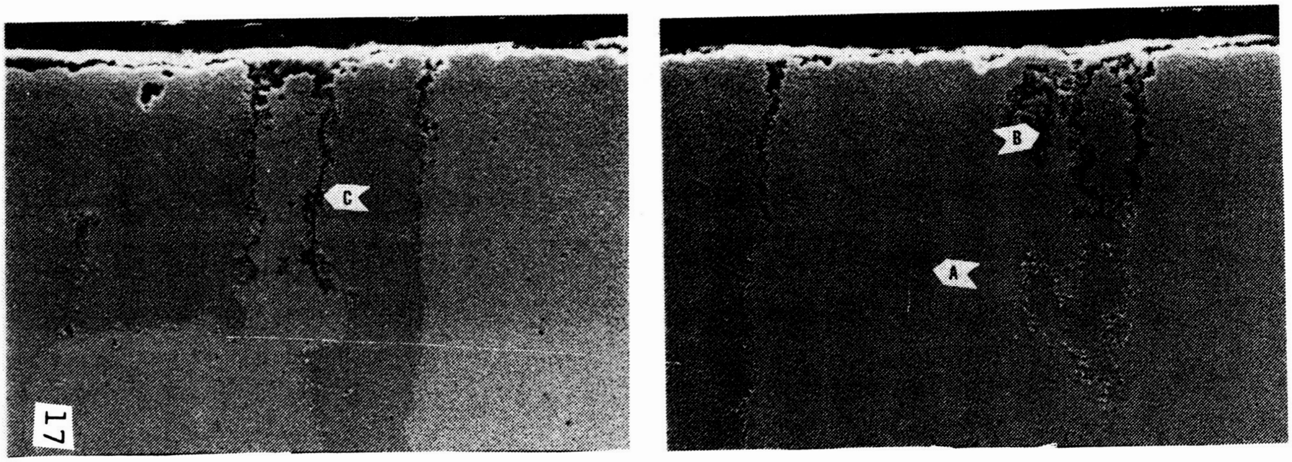

Figure 23. SEM Micrograph of Grain Boundary Oxidation in MA6000 Blade After 200-Hour Engine Test.

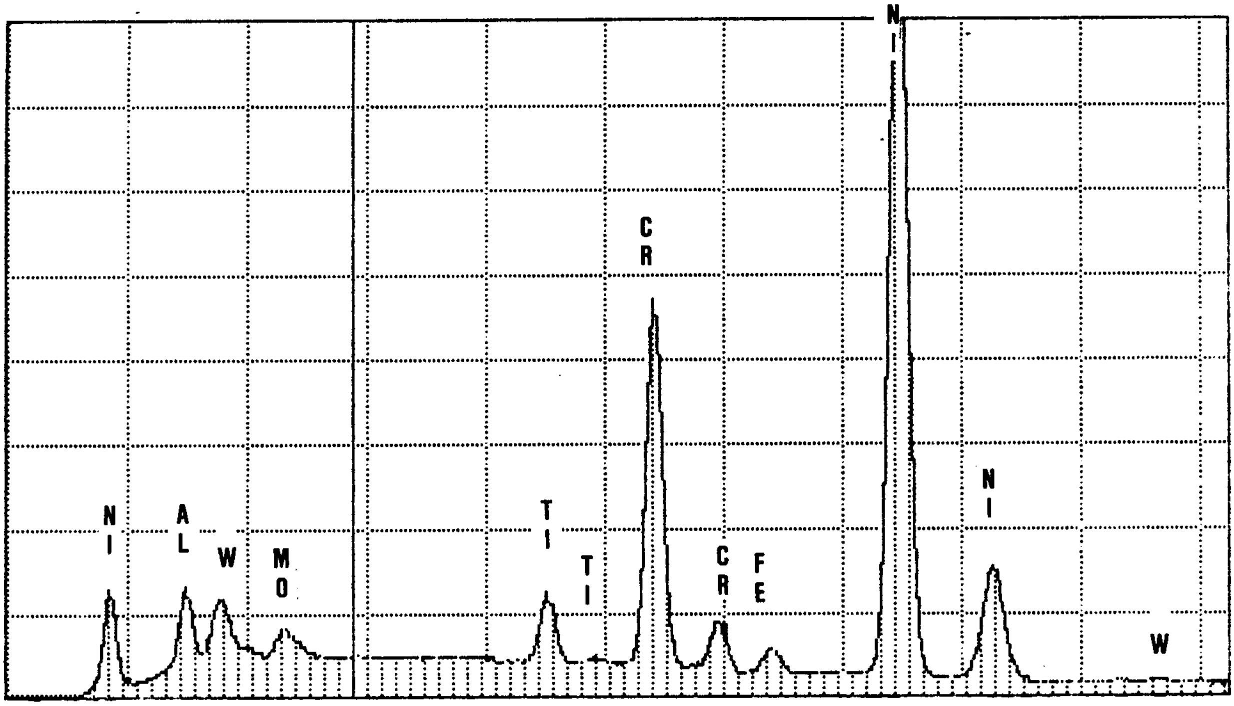

Figure 24. EDAX Spectrum of MA6000 Matrix at Location A in Figure 23.

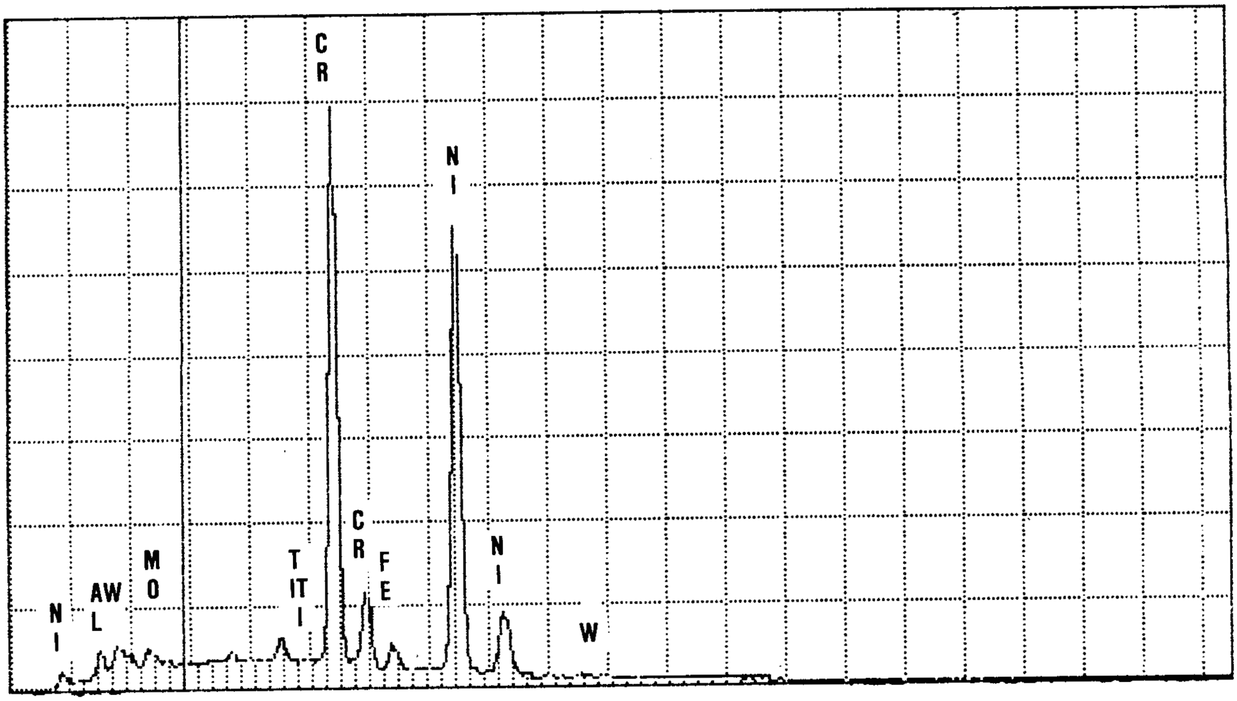

Figure 25. Typical EDAX Spectrum of MA6000 at Oxidized Region at Locations B and C in Figure 23 Showing High Cr Level.

SECTION V

5.0 CONCLUSIONS

The following conclusions are based upon the results of the engine testing and posttest analysis of the MA6000 turbine blades presented in this report.

- MA6000 turbine blades are capable of operating in an engine environment such as was demonstrated by the high-cycle fatigue, stress rupture, simulated mission, and low-cycle fatigue testing.

- MA6000 is not as oxidation resistant as MAR-M 247. This was confirmed by the intergrannular oxidation observed after the testing.

- MA6000 will require oxidation protection such as NiCrAlY coatings if it is to survive in a long-term engine operating environment.

- The fretting observed on the bearing surfaces of the MA6000 blade attachments was unusual, but not excessive. This fretting is believed to be related to design parameters such as high bearing stresses, rather than a material characteristic.

SECTION VI

6.0 RECOMMENDATIONS

After completion of the engine testing and the posttest evalution of the MA6000 turbine blades, the following recommendations can be made:

- o Consider MA6000 blades for future applications where uncooled, high temperature operation is the primary consideration.
- o MA6000 alloy operating in a long-term engine operating environment should be coated with an oxidation resistant coating such as NiCrAlY. This can be overlayed with CoCrAlY if hot corrosion conditions are anticipated.
- o Evaluate method(s) to alleviate firtree fretting on the MA6000 blades.

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16. Abstract
The overall objective of Project 4 was to develop a high-temperature, uncooled gas turbine blade using MA6000 alloy from the feasibility stage through the engine demonstration test.

The program objectives were achieved. Production scale up of the MA6000 alloy was achieved with a fair degree of tolerance to non-optimum processing. The blade manufacturing process was also optimized.

The mechanical, environmental, and physical property evaluations of MA6000 were conducted. The ultimate tensile strength, to about 704C (1300F), is higher than DS MAR-M 247 but with a corresponding lower tensile elongation. Also, above 982C (1800F) MA6000 tensile strength does not decrease as rapidly as MAR-M 247 because the ODS mechanism still remains active. Based on oxidation resistance and diffusional stability considerations, NiCrAlY coatings are recommended. CoCrAlY coating should be applied on top of a thin NiCrAlY coating if hot corrosion is expected.

Vibration tests, whirlpit tests, and a high-rotor-rig test were conducted to ensure successful completion of the engine test of the MA6000 TFE731 high pressure turbine blades. The results of these tests were acceptable. Successful completion of the engine test verified these test predictions.

In production quantities, the cost of the Project 4 MA6000 blade is estimated to be about twice that of a cast DS MAR-M 247 blade.

17. Key Words (Suggested by Author(s))
Turbine-Blade
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