WL-TR-94-2092

RECIRCULATING CAVITY CASING TREATMENT FAILURE

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AUG 1994

FINAL REPORT FOR 04/01/93 - 02/01/94

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NOTICE

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1994

3. REPORT TYPE AND DATES COVERED
FINAL April 1993 to February 1994

4. TITLE AND SUBTITLE
Recirculating Cavity Casing Treatment
Failure

5. FUNDING NUMBERS
PE: 62203F
PR: 3066
TA: 17
WU: 91

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Wright Laboratory
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7650

8. PERFORMING ORGANIZATION REPORT NUMBER
WL-TR-94-2092

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Aero Propulsion & Power Directorate
Wright Laboratory
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7650

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
WL-TR-94-2092

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As part of the Augmented Damping of Low Aspect Ratio Fans (ADLARF) program at the Compressor Research Facility (CRF), the Recirculating Cavity Casing Treatment was in test operation. The casing treatment was made of 6061-T6 aluminum alloy and was specially instrumented for the exploration of stall margin, performance data, and thermal effects. In addition to obtaining stall margin data, this casing treatment was part of a detailed test program to study the effects of five different casing treatments. After thermal cycling the casing treatment between ambient temperature and 650°F, the casing treatment failed after seven hours of test time. The casing treatment was removed and a failure analysis was performed. This paper will summarize the study findings and conclude with recommended actions.

14. SUBJECT TERMS
Recirculating Cavity Casing Treatment
Stall Margin
Thermal Fatigue
Axial Compressor

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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ABBREVIATIONS

ADLARF	Augmented Damping of Low Aspect Ratio Fans
CRF	Compressor Research Facility
DV	Discharge Valve
FDA	Fan Durability Assessment
GEAE	General Electric Aircraft Engines
GESRo	General Electric Swept Rotor
hrs	Hours
HTSC	High Tip Speed Compressor
Ksi	1,000 Pounds Per Square Inch (PSI)
Max	Maximum
min	Minutes
R_E	Rockwell E
rpm	Revolutions Per Minute
SSDP	Steady-State Data Point
UTR	Universal Temperature Reference
WPAFB	Wright-Patterson Air Force Base

SECTION 1
INTRODUCTION

On 17 and 18 May 1993, as part of the Augmented Damping of Low Aspect Ratio Fans (ADLARF) program at the Compressor Research Facility (CRF), the Recirculating Cavity Casing Treatment was in test operation according to the detailed Test Plan for the ADLARF compressor rig[1]. The CRF is part of the Air Force Aero Propulsion & Power Directorate complex located in Area B of Wright-Patterson Air Force Base (WPAFB), Ohio. The facility supports the exploratory and advanced development programs of the Turbine Engine Division. It can also be made available for use to other government and industry customers. Fully automated, state-of-the-art computer controls allow detailed study of steady-state and transient compressor phenomena with immediate data analysis. The casing treatment was made of 6061-T6 aluminum alloy and was specially instrumented for the exploration of stall margin, performance data, and thermal effects. In addition to obtaining stall margin data, this casing treatment was part of a detailed test program to study the effects of five different first stage casing treatments.

On 17 May 1993, the Test Article was tested for 1 hour and 53 minutes using clean inlet, no distortion screens. During this time, there were six full speedlines to stall at 98.6% speed, design speed, and two full speedlines to stall at 85% speed. The Recirculating Cavity Casing Treatment experienced thermal cycling where metal temperatures were observed between 250°F and 510°F during this portion of testing.

During the morning of 18 May 1993, the Test Article was boroscoped with no visual problems seen. Later the same day, the Test Article was tested for 3 hours and 37 minutes. During this time, there were eight full speedlines to stall at 68% speed and six full speedlines to stall at 85% speed. A Universal Temperature Reference (UTR) system is used at the CRF to maintain data integrity of the thermocouples. While at 85% speed, one of the UTR systems became inoperable. This system was connected to the temperatures on the Recirculating Cavity Casing Treatment. The decision was made to test without these temperatures in order to save valuable test time. After clean inlet testing with the Recirculating Cavity Casing Treatment was completed, a Tip Radial Distortion Screen was installed to analyze its effects on stall margin. A patch panel was reseated to correct the problem with the malfunctioned UTR system. The Test Article was tested for 1 hour and 44 minutes using this inlet configuration. During this time, there were three full speedlines to stall at 68% speed. Again, thermal cycling was observed with metal temperatures ranging from 320°F to 650°F.

On 19 May 1993, the Test Article was boroscoped. The Recirculating Cavity Casing Treatment was found to be extremely discolored from the heat and some of the fingers were cracked. The casing treatment was removed and an overall view of the 6061-T6 aluminum alloy casing treatment can be seen in Figure 1.

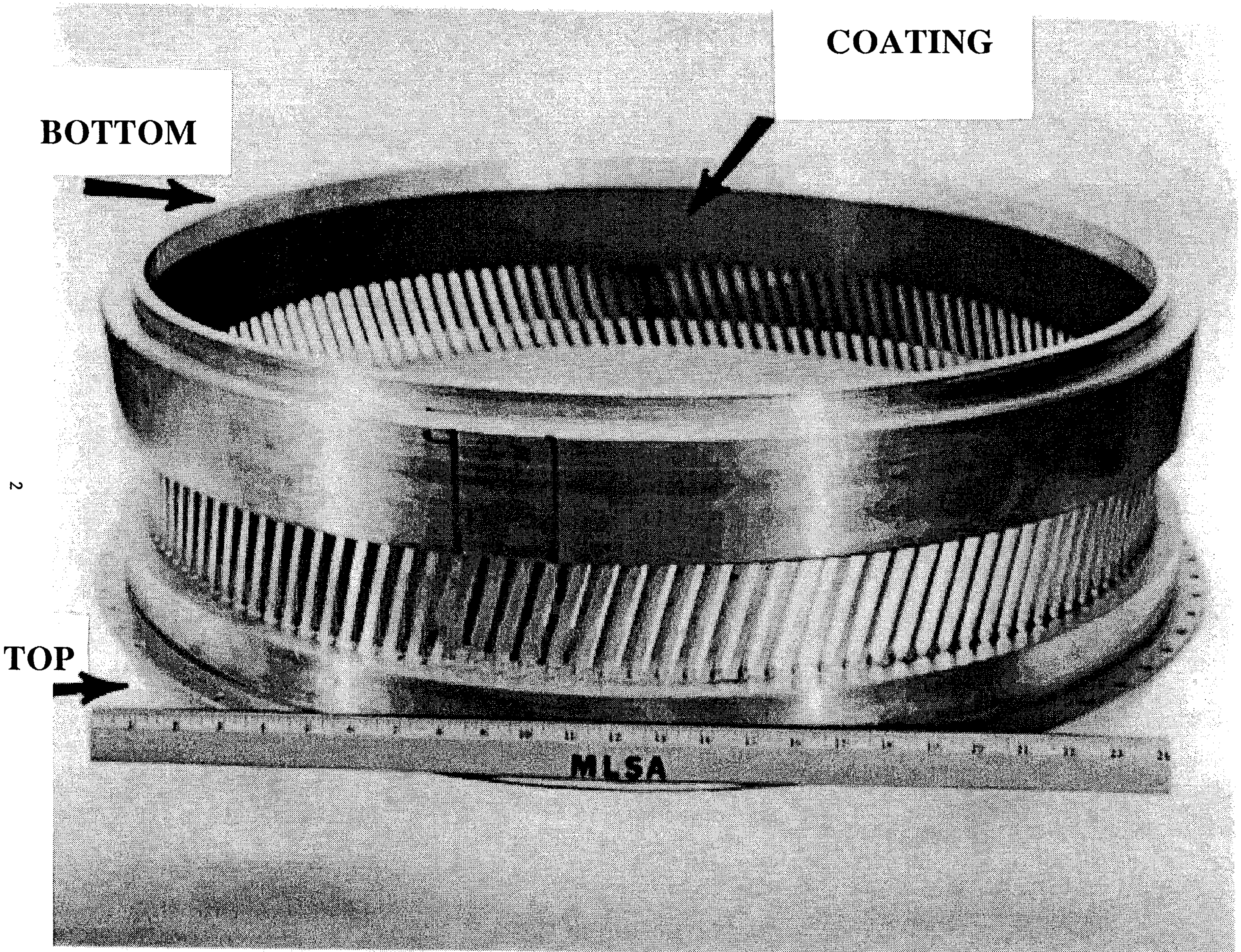

Figure 1 Overall View of the 6061-T6 Recirculating Cavity Casing Treatment

Overview

Section 1 presents the description of the Test Article, description of the Recirculating Cavity Casing Treatment, and a background on casing treatments. Section 2 addresses the chronology of the failure. Following this discussion, the failure analysis is introduced in Section 3 where the Materials Directorate at WPAFB and the University of Dayton Research Institute were instrumental in this evaluation. Finally, Section 4 summarizes the study findings and concludes with recommended actions.

Test Article Description

The ADLARF two-stage fan, shown installed in the CRF in Figure 2, was designed and fabricated by General Electric Aircraft Engines (GEAE). The ADLARF fan is a research rig, the primary objectives being to advance the state-of-the-art predictive techniques for fan blade forced response, blisk damping methodology, flow predictions, and casing treatment design for stall margin improvements.

The ADLARF Test Article utilized three different first stage blisks. The rig is a two-stage fan design without inlet guide vanes and utilizes variable first stage stator vanes for optimum performance. The three blisks scheduled for the ADLARF rig were the Fan Durability Assessment (FDA) blisk, the General Electric Swept Rotor (GESRo), and a modified version of the original High Tip Speed Compressor (HTSC) blisk.

Recirculating Cavity Casing Treatment Description

Angled slots above the first stage rotor tip join the flow path to a circumferentially continuous cavity radially beyond the slots. This is shown schematically in Figure 3. This new concept in casing treatments is made out of 6061-T6 aluminum alloy and provides 0.22-inch "fingers" above the rotor angled 15° to the axial direction. These fingers are also angled 50° to the radial direction and provides a recirculation cavity above the rotor of about 3.5 inches.

The ADLARF forward case is a one-piece steel cylinder enclosing the first stage rotor. The case is of sufficient inner dimension to allow easy insertion and removal of the first stage rotor Recirculating Cavity Casing Treatment. The forward case has two instrumentation "windows" (2.4" x 6.2" and 1.2" x 6.2") allowing for direct access to the first stage rotor flow field for several instrumentation systems. For the ADLARF test, the forward case was oriented with the large and small windows at 80 and 250°, respectively, from top center (clockwise, aft looking forward).

Background

It is known the casing treatment is effective in improving stall margin of axial-flow compressors or fans. On the other side, however, it is also known the casing treatment usually has an adverse effect on efficiency.

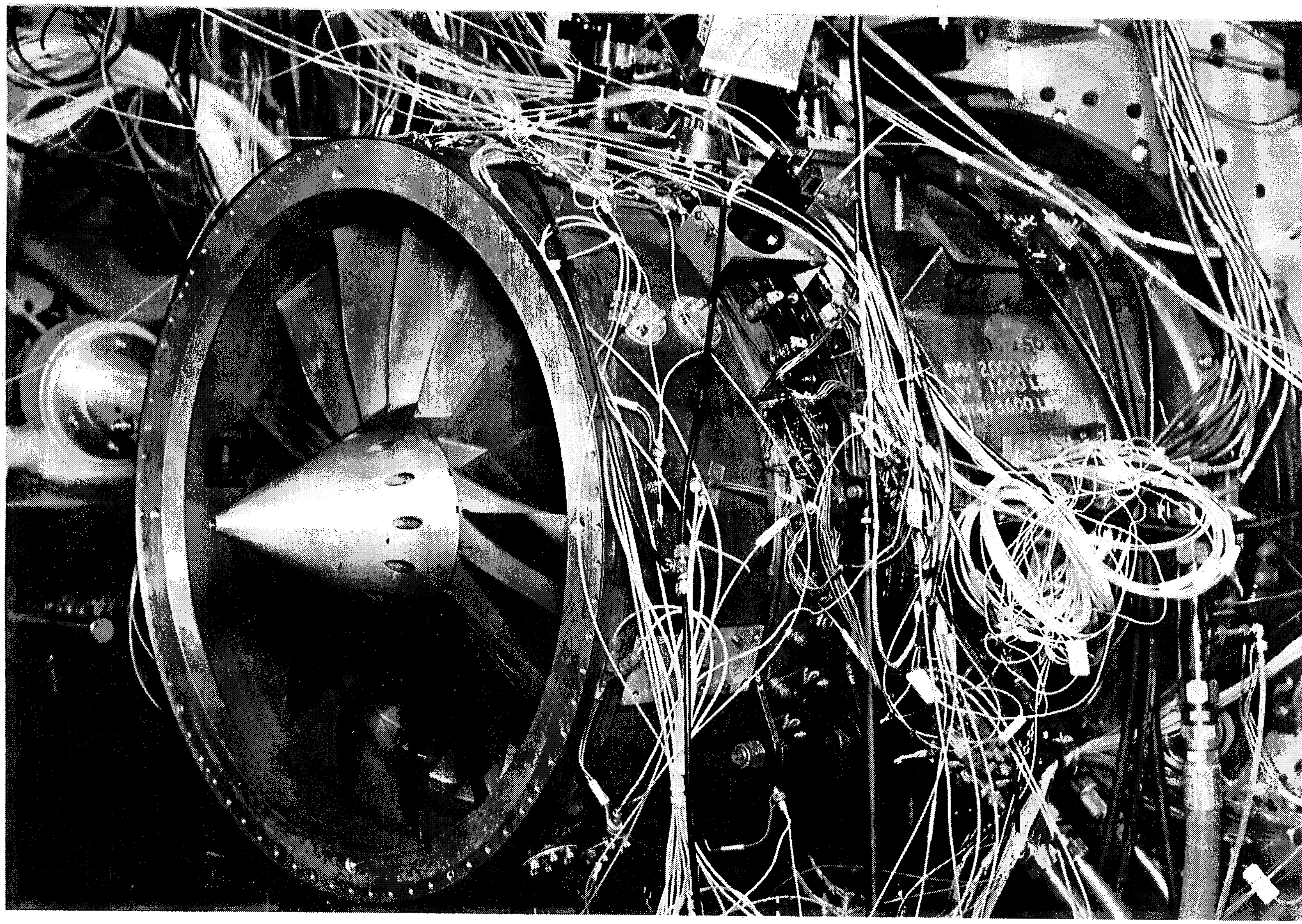

Figure 2. ADLARF Installed in Test Chamber

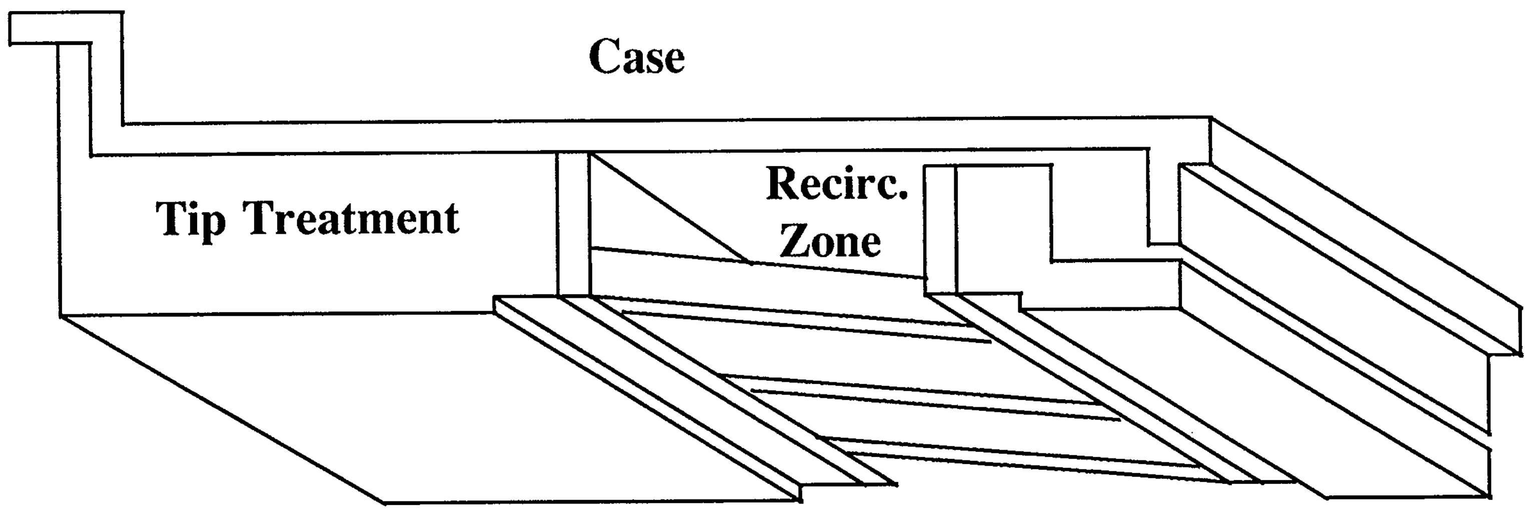

Figure 3 Schematic of Recirculating Cavity Casing Treatment

From the viewpoint of designing compressors, the most desirable configurations are ones improving stall margin to the maximum degree with the least lowering of efficiency. Many experiments have been carried out looking for these favorable treatment configurations, and many results on each particular configuration are reported. From these results, the general trend of the effectiveness of the casing treatment may be summarized as follows: configurations with axial slots, i.e. axial-skewed slots or axial-radial slots are generally effective in improving stall margin, but inevitably they lower the compressor efficiency to some extent. Meanwhile, configurations with circumferential grooves usually have the least adverse effects on the efficiency, but improve the stall margin only to a limited extent. It has been said for the former type of configurations, it is effective in suppressing the degree of efficiency lowering to limit the axial extent of the slots to some central regions of the axial projection of the rotor blade tip sections, or to insert suitable baffle plates in the slots in order to limit the quantities of a recirculating flow which appears in the slots. It has also been suggested, for the latter type of treatment configurations, putting several baffles in circumferential grooves may be effective in increasing stall margin[2].

In response to some interest in conducting a test using a casing treatment similar to the Russian Isotov RD-33 engine, the Turbine Engine Division looked into a potential design for the ADLARF test. The two fans are similar in diameter and flow size but different enough so the Recirculating Cavity Casing Treatment cannot be slipped directly into the ADLARF fan. The ground rules were to produce a design preserving the physics of the Recirculating Cavity Casing Treatment and keep fabrication time to a minimum. The physics being preserved is the ratio of the open area of the case to the closed area of the case. Keeping the fabrication time to a minimum is the main reason the material chosen for this application was 6061-T6 aluminum alloy. A secondary reason is because it was readily available in the machine shop where the casing treatment was fabricated.

SECTION 2
CHRONOLOGY OF THE FAILURE

The test program for the Recirculating Cavity Casing Treatment had one major objective: to determine the stall margin/efficiency trade-off of the five different casing treatments.

The ADLARF rig with the Recirculating Cavity Casing Treatment installed was operated above 3,544 rpm, Minimum Speed, for a total time of 7 hours and 14 minutes. During this time, there were six full speedlines to stall at 98.6% speed, eight full speedlines to stall at 85% speed, and 11 full speedlines to stall at 68% speed. The casing treatment was thermally cycled from temperatures ranging from 250°F to 650°F. Each run was now broken down chronologically, below.

On Run 35, 17 May 1993, the ADLARF rig reached Minimum Speed at 21:05 using the clean inlet system. The Test Article reached 98.6% speed at 21:21 and the Discharge Valve (DV) was throttled to peak efficiency and a Steady-State Data Point (SSDP) was taken. From there, the DV was throttled to stall at 0.1°/second. The peak efficiency SSDP was repeated at 21:39. While trying to locate a near stall SSDP, we fell into stall. At 21:44, we observed the metal temperatures above 505°F. After setting a new vane schedule, the same procedure for obtaining speedlines were followed. This process was repeated one more time at 98.6% speed with the metal temperatures over 600°F. The Test Article was then brought to 85% speed where one full speedline to stall was performed. A normal shutdown was initiated at 22:58. During this run, the metal temperatures ranged from 250°F to 650°F and the Test Article was above Minimum Speed for 1 hour and 53 minutes.

On Run 36, 18 May 1993, the ADLARF rig reach Minimum Speed at 16:03 using the clean inlet system. The Test Article reached 98.6% speed at 16:05 and the standard checkpoint was taken. The rig was then taken to 68% speed and six full speedlines to stall were obtained. At 18:45, the UTR system for the Recirculating Cavity Casing Treatment metal temperatures failed and the test continued without metal temperature monitoring because the Test Article was operating at a low speed and the last observed metal temperatures were only 450°F. Two more full speedlines to stall were obtained and a checkpoint at 98.6% speed was repeated before the normal shutdown at 19:42. Total operating time above Minimum Speed was 3 hours and 37 minutes.

Since clean inlet testing was complete, the Tip Radial Distortion Screen was installed for Run 37, 18 May 1993. The ADLARF rig reached Minimum Speed at 20:56 and then 98.6% speed at 21:01. While obtaining the checkpoint, the metal temperatures had already risen to over 510°F. The rig was then taken to 85% speed and three full speedlines to stall were performed. A normal shutdown was initiated at 22:42. Total operating time above 3,544 rpm was 1 hour and 44 minutes with metal temperatures reaching a maximum of 550°F. Total operating above Minimum Speed is summarized in Table 1.

TABLE 1 Operating Time with Test Article Above 3,544 rpm

Run Number	Inlet Condition	Test Article Speed (rpm)	Max Metal Temp (°F)	Time (hrs:min)	Sub Total (hrs:min)
35	Clean	13,115	650	01:20	01:20
35	Clean	11,295	505	00:20	01:40
36	Clean	13,115	N/A	00:18	01:58
36	Clean	11,295	N/A	01:14	03:12
36	Clean	9,035	N/A	01:55	05:07
37	Tip Radial	13,115	550	00:18	05:35
37	Tip Radial	11,295	515	00:27	06:02
37	Tip Radial	9,035	496	00:58	07:00

On 19 May 1993, the Test Article was boroscoped to find cracked fingers on the Recirculating Cavity Casing Treatment. See Figure 4. The casing treatment was then removed and failure analysis was started.

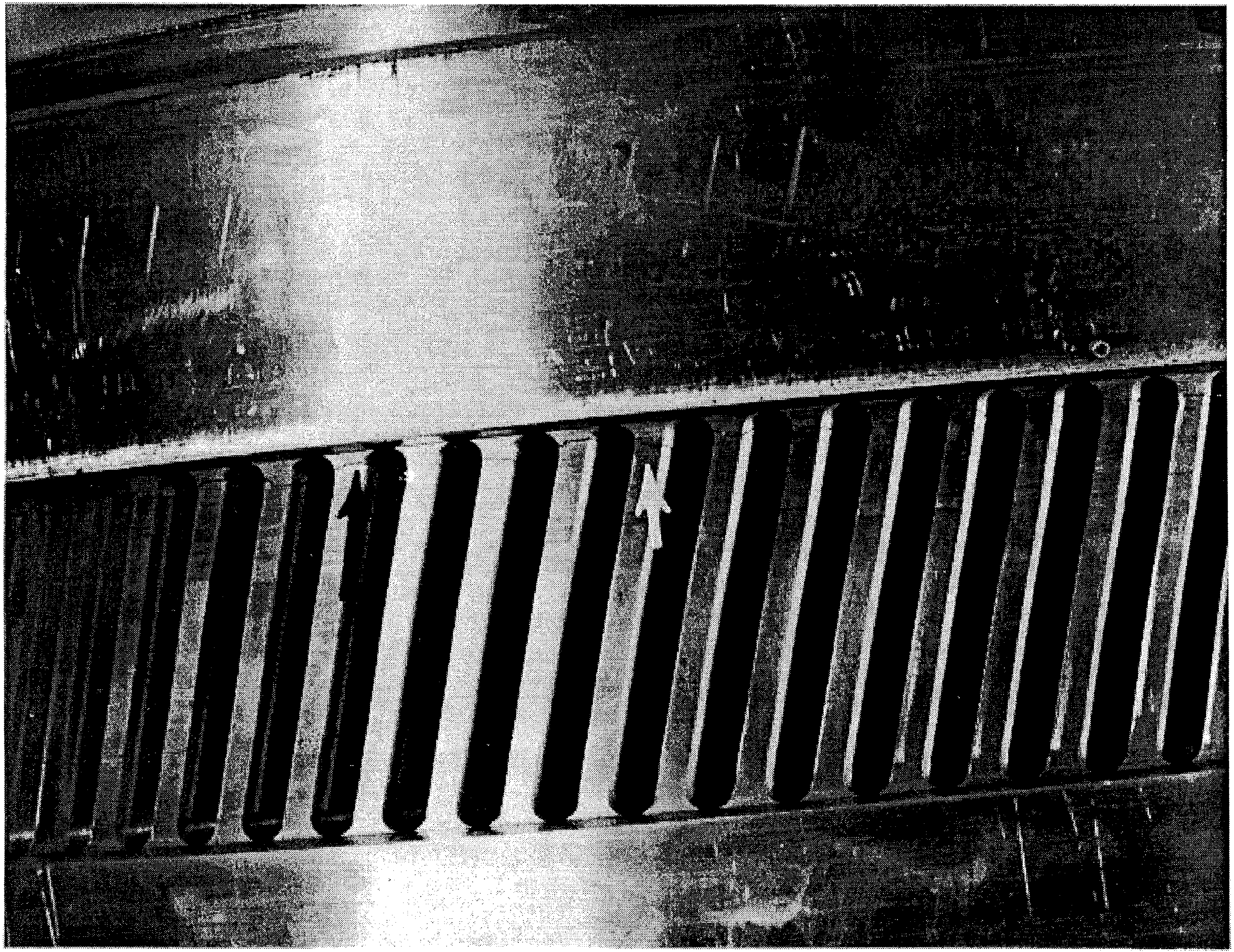

Figure 4 Photograph of the Cracked Fingers

SECTION 3
FAILURE ANALYSIS

After the Recirculating Cavity Casing Treatment was removed, it was taken to the Materials Directorate Systems Support Division at WPAFB to begin the failure analysis. Also involved in the failure analysis was the University of Dayton Research Institute.

After reviewing Figure 4, it can be seen only one end of the fingers developed cracks. This end is the downstream end of the casing seeing the hottest air flow. Cracks appear to originate from the two corners of the fingers, the corner being the intersection of the width and the thickness dimension of a finger. A close-up view of a crack in the finger can be seen in Figure 5. Scanning electron microscopy, Figure 6, determined these corner cracks to be due to mechanical fatigue. Scanning electron micrographs show fatigue striations indicative of mechanical fatigue, Figures 7 and 8.

Hardness measurements on the cracked fingers showed substantial variation along the length of the finger. In the area where the fracture occurred, the hardness is Rockwell E (R_E) 67. In the middle of the finger, the hardness is R_E 63. The area at the bottom of the finger farthest from the fracture site is R_E 78. The minimum recommended hardness according to the American Society for Testing Materials Specification 2658 for 6061-T6 is R_E 85. The original design specifications did not call out a minimum desired R_E hardness value. The decreased hardness numbers are due to the extreme temperatures seen by the casing treatment.

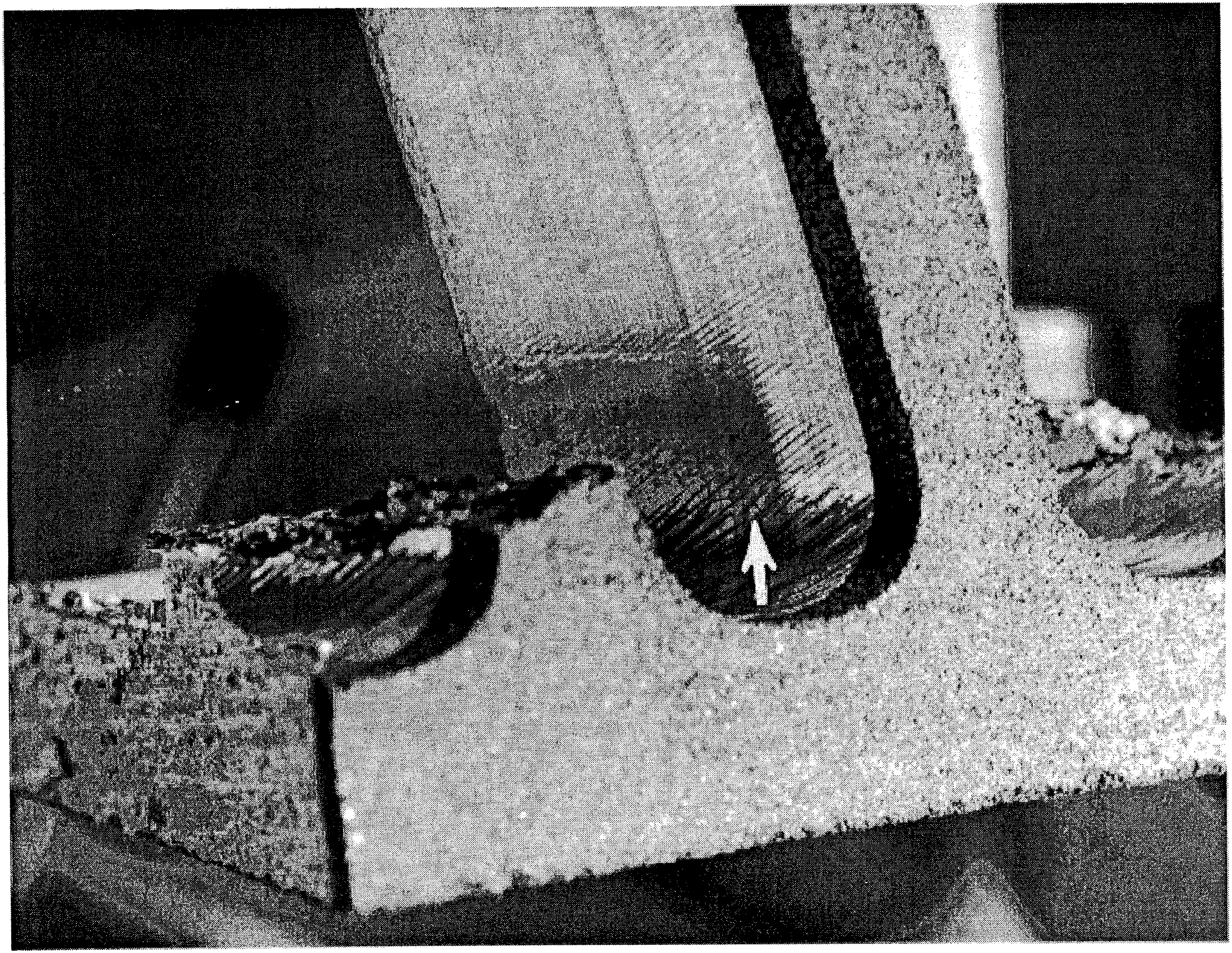

Figure 5 Close-Up View of a Cracked Finger

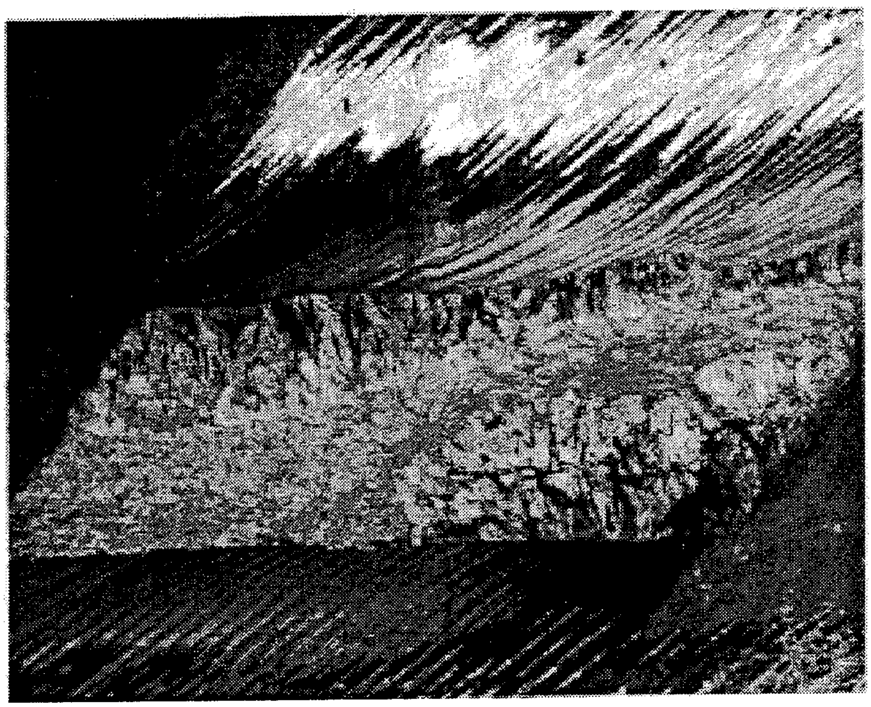

Figure 6 Optical Micorgraph Depicting Two Corner Cracks
Mag: 7.2X

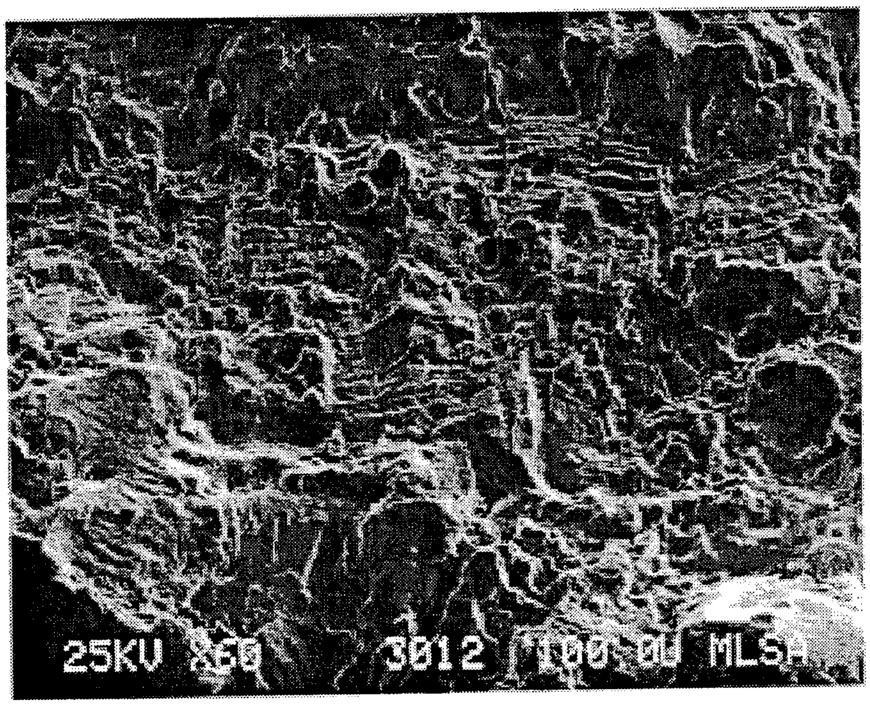

Figure 7 Scanning Electron Micrograph Fatigue Striations
Mag: 60X

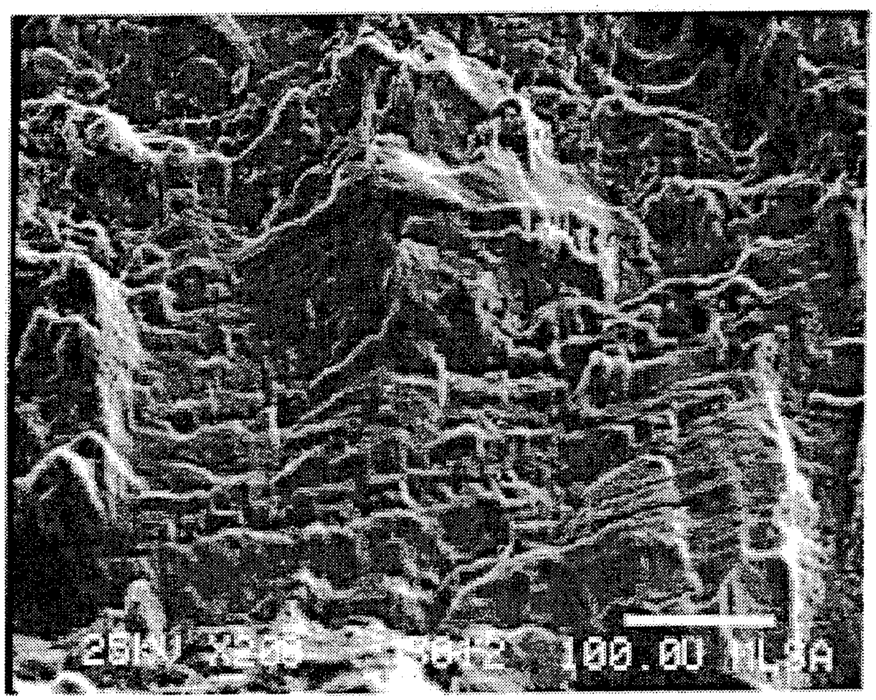

Figure 8 Higher Magnification View of Figure 7
Mag: 200X

SECTION 4
CONCLUSIONS/RECOMMENDATIONS

All of the hardness numbers along the finger length were lower than the minimum recommended number of R_E 85 for 6061-T6. This would suggest the aluminum alloy softened due to exposure to high temperatures. Aluminum 6061-T6 will soften when exposed to temperatures greater than 300°F. Although the hardness in the middle portion of the finger is lowest, cracks did not originate in this region. The presence of a sharp radius at the junction and a low hardness caused the failure.

Almost all of the cracked fingers exhibited corner cracks. The corner cracks were initiated and propagated by fatigue. Fatigue crack propagation data for 6061-T6 are available only for room temperature and 300°F temperatures. These data show at 300°F, fatigue crack growth rates are twice as fast as at room temperature. This suggested exposure to higher temperatures would only be further detrimental to crack propagation. Data on yield strength show 30 minutes exposure to 300°F decreases the yield strength from 42 Ksi to 36 Ksi. This would also imply reduced hardness.

Since fatigue cracking of the fingers is related to softening of the aluminum alloy, it is recommended 6061-T6 aluminum alloy not be used for this application.

Aluminum alloys 2219 and 2618 have better fatigue crack growth resistance under prolonged exposures between 300°F and 600°F and should be considered as alternate materials.

Although the suggested replacement aluminum alloys would work under the conditions specified and are lightweight, they are expensive and not readily available to a test program already on a tight time constraint. Since weight is not important in a ground test, the plain carbon steel 4041 will handle the rugged test environment, is available in stock at most metal distributors, and is easily machined.

It is also the recommendation of the paper to fully instrument the new casing treatment with thermocouples to analyze the effect of the elevated temperatures. Since the cracks occurred in the corners, it was suggested to increase the radius of the corners. This will also shorten the total machining time.

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[1] Captain Patrick L. Morrow, Detailed Test Plan for the General Electric Aircraft Engines Augmented Damping of Low Aspect Ratio Fans (ADLARF), 1 April 1993

[2] Greitzer, E.M., Nikkanen J.P., and Haddad, D.E., 1979, "A Fundamental Criterion for the Application of Rotor Casing Treatment," ASME Journal of Fluids Engineering, Vol. 101, pp. 237-244