NASA/TM—1999-209147

Measurement of Plastic Stress and Strain for Analytical Method Verification

(MSFC Center Director's Discretionary Fund Final Report, Project No. 93–08)

J.M. Price, B.E. Steeve, and G.R. Swanson
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center

February 1999

Available from:

NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090–2934
(301) 621–0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487–4650

TABLE OF CONTENTS

LIST OF FIGURES

TECHNICAL MEMORANDUM

MEASUREMENT OF PLASTIC STRESS AND STRAIN FOR ANALYTICAL METHOD VERIFICATION (MSFC Center Director's Discretionary Fund Final Report, Project No. 93–08)

I. INTRODUCTION

Currently on the Space Shuttle Main Engine (SSME) and Alternate Turbopump Development (ATD) programs, a great deal of effort is spent calculating and predicting plastic strains, residual stresses, and fatigue life after plastic deformation. These conditions result from welding, bolt overtorquing, dimensional mismatches causing assembly stresses, anomalous loadings, thermal loadings, and nominal hot fire. The validity of analytical solutions to these problems is often in question, particularly finite element models and associated material models.

II. OBJECTIVE

The objective of this proposal is to model and test a common engine material to develop a set of test data and specific material properties to be input to analytical solution routines as a verification method. This would provide a fixed reference to apply to new analytical techniques and computer routines that become available. This will also provide valuable hands-on experience with experimental stress analysis techniques not commonly used at Marshall Space Flight Center (MSFC) to measure plastic effects, and experience with matching nonlinear analysis with measured nonlinear data. It is not possible to measure plastic strains on most structures due to complex engine loading and geometry, so having controlled tests and measurements would be invaluable for validating analytical techniques.

III. APPROACH

The approach for this Center Director's Discretionary Fund (CDDF) was altered from the use of laboratory specimens when an impeller failure in an AT high-pressure fuel turbo pump (HPFTP) for the SSME provided the opportunity to model and measure plastic stress and strain directly on actual engine hardware.

IV. IMPELLER FAILURE INTRODUCTION

The AT/HPFTP is being developed by Pratt and Whitney (PW) for NASA MSFC, and will replace the current HPFTP (built by Rocketdyne) on the SSME as part of a block change upgrade with the first flight scheduled for late 1999. The AT/HPFTP incorporates new bearing and turbine material technologies along with improved manufacturing techniques, developed since the original HPFTP's design in the early 1970's. The HPFTP is a turbine and pump on a single shaft that operates at 37,000 rpm, providing the SSME with 68 kg/sec (150 lb/sec) of liquid hydrogen at 41.37 MPa (6,000 psia) and 53 K (96 R) when the engine is at 109-percent rated power level (RPL).

The AT/HPFTP is designed to provide substantially longer life between overhauls and minimal inspection between flights. The design requirements are 60 flight equivalents (engines are tested for a full-duration mission on the ground before acceptance for flight) with an analytical safety factor of 4. The current pump requires detailed inspections between flights and complete overhaul after only 5,000 seconds of operation.

An early development version of the HPFTP experienced a failure in the pump's third impeller shroud and third impeller first splitter blade. Pieces of the titanium impeller were liberated and subsequently lodged downstream in the flow path. The failure occurred in a low time unit with only 10 starts and 1,991 sec of operational experience. A fuel pump failure can cause a catastrophic failure of the engine system since it will leave the engine to run oxygen-rich. In the moments it takes the engine system to detect and react to the pump failure by shutting down the engine, the oxygen-rich condition can raise temperatures and pressures beyond the combustion limits of the materials in the engine.

An investigation team was tasked with explaining how the failure initiated, propagated to part liberation, and how to avoid this in production hardware. Due to the severe environment and tight space limitations inside the turbopump, direct measurements of the stresses and strains on the impeller during operation were not possible. It was also not possible to economically duplicate the impeller boundary conditions in a laboratory rig, so only postengine test-run hardware was available for examination. Residual stress measurements provided confirmation of analytical predictions of the most probable failure mode.

V. HARDWARE DESCRIPTION

The failed impeller is the third stage of the pump side of the AT/HPFTP (see cross section in fig. 1 for location). It is machined from an A110 extra-low interstitial (ELI) titanium forging. Tungsten carbide coatings were applied to the rub stop surfaces to protect the titanium from direct contact with stelite surfaces on the mating face seals. An inlet and side view of the impeller are shown in figure 2. Identified in the figure are the posttest crack locations and the location of the rub stops. The cracks in the shroud initiated at the outer diameter corner of the rub stop and progressed up to 22 mm (0.85 in.).

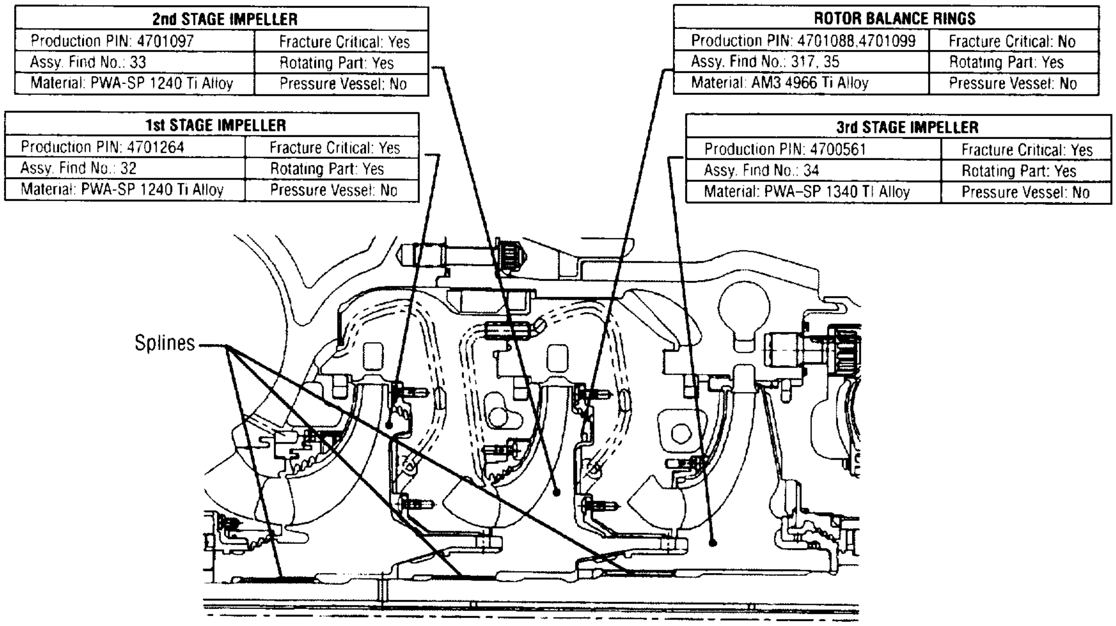

Figure 1. Cross section of the Pratt and Whitney AT/HPFTP pump end showing the impeller locations.

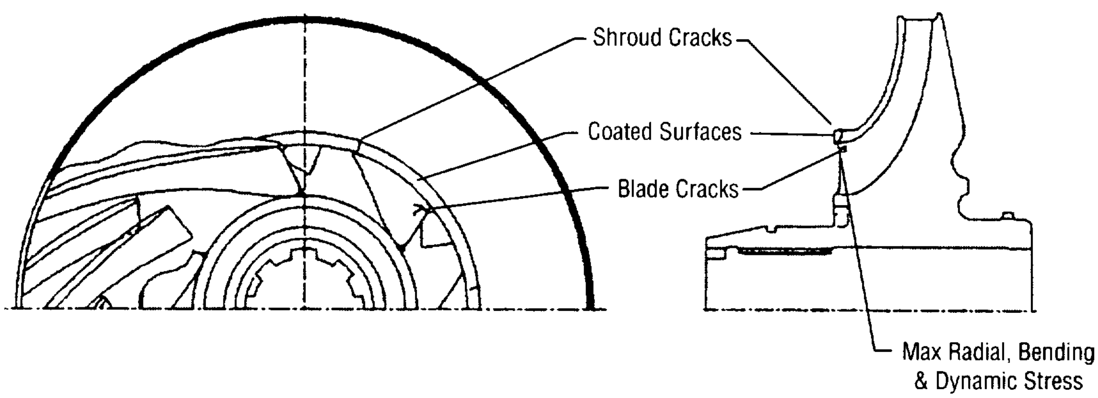

Figure 2. Third impeller end and section views showing crack locations.

During operation of the pump, the upstream and downstream faces of the third impeller are used as thrust pistons to provide axial thrust balance. This axially positions the shaft and reacts the turbine axial blowdown loads. During engine start and shutdown, the thrust balance system momentarily lacks the hydrogen pressure to axially position the shaft. During these short-duration transients, <0.2 sec, the axial loads are reacted through the rub stops.

VI. FAILURE INVESTIGATION

The failure investigation team, as reported by reference 1, identified the following scenario as most probable:

- The third impeller pump side rub stop contacts the stelite stationary seal during start transients. Stelite is displaced at the outer diameter which aggravates rub damage to the impeller rub stop.

- Frictional heating during rub yields the titanium in compression.

- After the pump speed builds, the thrust balance system lifts the rub stop, quenching the hot titanium in liquid hydrogen. This causes high tensile stresses and initiates the crack.

- The crack is driven to critical length by repeated start/rub/quench cycles.

- When the flaw has grown to critical length, the shroud fractures to the final crack length.

- The loss of hoop continuity at the shroud inlet raises the first splitter blade stresses (>1,792 MPa, 260 KSI).

- The blade crack initiates and grows to separate the titanium pieces found downstream in the engine system.

Microstructural evaluation of the hardware[2] showed that the titanium material at the rub stop had experienced temperatures >1,311 K (1,900 °F) evidenced by changes in the phases of the microstructure. The temperatures were below <1,844 K (2,860 °F) since melting of the titanium was not observed. The tungsten carbide coating was heat-checked and missing small pieces.

Thermal analysis of the frictional heating by Goode[3] predicted peak titanium temperatures of 1,667 K (2,540 °F) during the rub event. The temperature profile with depth from the surface was steep, decaying to 138 K (–210 °F) 1.27 mm (0.05 in.) below the surface.

A finite element model (FEM) of the local region of the rub stop was run using nonlinear material properties and the thermal profiles generated by Goode[3]. The resulting rub stop surface plastic stress versus strain cycle is shown in figure 3. The model was run for two cycles, which showed the stress strain hysteresis loop to be established. Note that the first cycle start point is at zero stress and strain, and during the peak rub, a 1.4-percent compressive strain is developed. The hoop stress is rather low since the titanium's Young's modulus has dropped, due to the high local temperature. At steady state operation, a very high hoop stress is present since the compressive yielded titanium is now being cooled by the hydrogen. The end of the first cycle is when the engine is shut down and the impeller returns to room temperature; this is also the starting point for the second cycle. Note the high tensile residual hoop stress of 620 MPa (90 KSI). This residual stress is localized on the surface of the rub stop to a depth of 0.8 mm (0.03 in.), after which it decays rapidly with increasing depth. This corresponds to the depth of the heat-damaged region.

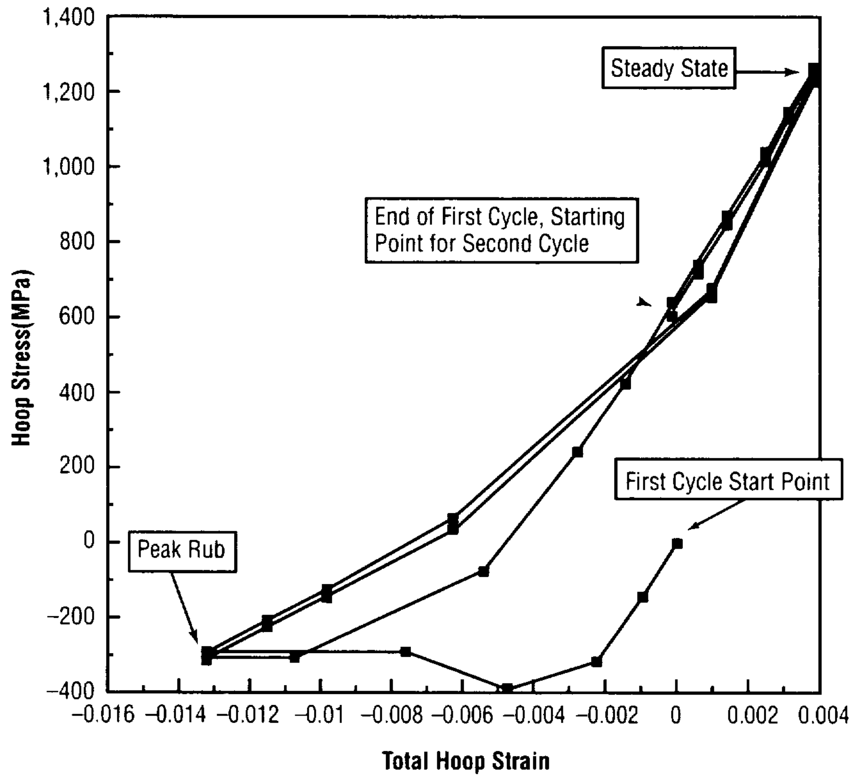

Figure 3. Results from nonlinear finite element analysis showing stress-strain hysteresis loop in AT/HPTFP third impeller pump side rub stop.

VII. EXPERIMENTAL RESULTS

To provide an anchor to all the assumptions used in the analysis of the pump side rub stop, a measurement of the residual stress was made. The method selected was the measurement of residual stress by the hole-drilling strain-gauge method. Due to the predicted shallow depth of the residual stress, the smallest diameter hole, 0.8 mm (0.031 in.), was selected so the depth drilled would be within the damage zone. This would avoid drilling into regions with large stress gradients which would complicate interpretation of the data.

A Measurements Group RS–200 optical milling guide, outfitted with the air turbine and a 0.79 mm (0.031 in.) carbide-tipped cutter, was used to drill the holes. Micro Measurements EA–06–031RE–120 hole drilling residual strain gauges were mounted on the rub stop face. This gauge is specified for the cutter used, and also fits within the narrow width of the rub stop, 6.35 mm (0.25 in.). These gauges are special three-element rosettes with 0.79 mm (0.031 in.) gauge lengths on a grid centerline diameter of 2.56 mm (0.101 in.), about where the hole center will be drilled.

The tungsten carbide coating is only a few tenths of a millimeter thick and was etched off before gauge application, since it was in poor condition and is difficult to drill through. Due to the crazed and spalled character of the remaining tungsten carbide coating, its removal would have no effect on the measurement of residual stress in the titanium. The specimen tested was a wedge cut from the failed impeller. Since the residual stress is local to the surface and reacted by the bulk of material beneath it, the loss of hoop continuity in the specimen is considered to have little effect. Additionally, the cracks in the shroud had effectively broken the hoop continuity. A gauge was also mounted on the side of the cut face of the rub stop to sample the residual stress field behind the plastic region.

The holes were drilled following the Measurements Group procedures,[4] and the data reduced, following Measurements Group and ASTM guidelines in references 4 and 5. Table 1 shows the experimental results. The equivalent uniform stress is defined in reference 4 as that stress magnitude which, if uniformly distributed, would produce the same total relieved strain, at any depth, as measured during hole drilling. The FEM-calculated residual stress for the pump rub stop is 620 MPa (90 KSI).

Table 1. Gauge locations and maximum equivalent stresses measured.

Gauge Location	Max. Equivalent Uniform Stress MPa (KSI)	
Pump rub stop	(99.6)	Hoop component
Pump rub stop	(53.7)	Hoop component
Cut face of rub stop	(–12.6)	Maximum
Turbine rub stop	(41.6)	Hoop component

VIII. CONCLUSIONS

The experimental data from the residual stress measurement compared favorably with the analytical predictions. This confirmed that redesigning the thrust balance system to accommodate the transient engine start and shutdown conditions without rub was the proper corrective action. The transient axial loads are now reacted in the pump end ball bearing at start and a separate IN 100 rub ring at shutdown. Subsequent pump builds have demonstrated the redesign's effectiveness at eliminating the frictional heating-induced cracking.

REFERENCES

1. Mills, D.K.: "HPFTP F6–3 Third Impeller Failure Investigation." PW Government Engines & Space Propulsion Report to NASA MSFC, April 1995.

2. Dills, M.: Investigation Briefing to NASA MSFC by PW, March 1995.

3. Goode, B.K.: "3rd Impeller Thermal Analysis." Unpublished work presented to NASA MSFC, March 1995.

4. Measurements Group, Inc., "Measurement of Residual Stresses by the Hole-Drilling Strain Gauge Method." Measurements Group Tech Note TN–503–3.

5. ASTM Standard E837–89, "Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gauge Method." ASTM, 1992.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1999	Technical Memorandum

4. TITLE AND SUBTITLE

Measurement of Plastic Stress and Strain for Analytical Method Verification (MSFC Center Director's Discretionary Fund Final Report, Project No. 93–08)

5. FUNDING NUMBERS

6. AUTHORS

J.M. Price, B.E. Steeve, and G.R. Swanson

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER

M—914

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA/TM—1999–209147

11. SUPPLEMENTARY NOTES

Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified—Unlimited
Subject Category 39
Nonstandard Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The analytical prediction of stress, strain, and fatigue life at locations experiencing local plasticity is full of uncertainties. Much of this uncertainity arises from the material models and their use in the numerical techniques used to solve plasticity problems. Experimental measurements of actual plastic strains would allow the validity of these models and solutions to be tested. This memorandum describes how experimental plastic residual strain measurements were used to verify the results of a thermally induced plastic fatigue failure analysis of a space shuttle main engine fuel pump component.

14. SUBJECT TERMS

plasticity, residual stress, space shuttle main engine

15. NUMBER OF PAGES 16

16. PRICE CODE A03

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. 239-18
298-102