LYCOMING SPECIAL CERTIFICATION REVIEW TEAM (SCRT)

Final Report

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Introduction

Over the period between October 2002 and October 2004, the Lycoming SCRT reviewed manuals, monitored engine tests, and evaluated computer-based engineering analyses in an effort to determine the root cause of service failures of Lycoming crankshafts made from the F13F17707 forging. The team's review encompassed the following four areas:

- Design and certification
- Installation and operation
- Stress, fatigue and fracture mechanics
- Metallurgical

These subjects, along with an overview of crankshaft design, history, manufacturing and the service problem are presented in this final report.

Investigation

The Lycoming SCRT was divided into four working groups to address the above issues:

- The Design/Certification Working Group was tasked with evaluating past and current design and certification processes at Textron Lycoming. To accomplish this, the group reviewed the certification process for the first Textron Lycoming TIO-540 engine, approved in 1965, and compared it to the present day type certification process. The group's efforts were directed at determining whether the old process was robust enough as compared to today's certification process requirements. The working group also evaluated the engineering design changes, manufacturing process changes, and supplier changes as applied to TIO-540 engine model crankshafts over the years to better understand the suitability of these other key elements of the design and certification process.

- The Installations/Operations Working Group was tasked with evaluating published data and procedures related to installation and operation of the Lycoming TIO-540 engine to determine if these could have any effect on the crankshaft failures. The working group reviewed engine and airplane manuals and engineering reports and conducted the on-site reviews with airplane manufacturers to accomplish this task.

- The Stress Analysis Working Group participated in engine and component testing, and the development of system dynamics, stress, fatigue and fracture mechanics computer models. These computer models were used to estimate the maximum operating stresses on critical areas of the crankshaft and then those stresses were used to determine the fatigue life of crankshafts manufactured from clean material and to assess the service life of crankshafts manufactured from honeycomb material.

- The Metallurgical Working Group reviewed Lycoming's examination of crankshaft material and performed their own independent exam and fatigue testing of crankshaft material to identify the cause of the defective material.

Key Lessons Learned

Key "Lessons Learned" are related directly to the root cause of the crankshaft service problem:

a. Lack of PAH Supplier oversight for critical processes: The primary contributor to the root cause of the crankshaft failures is lack of adequate supplier control by the PAH. Lack of adequate supplier control can result in process deviations that can have significant effects on the service life of critical reciprocating engine parts.
b. Changes to Critical Processes: The FAA does not have clear policies and guidance addressing substantiation of changes to critical processes, or changes in suppliers who perform critical processes. Confusion exists between what is covered in the type design and what is not.
c. Classification of Major Design Changes: Classification of major design changes and associated substantiation can vary widely amongst reciprocating engine manufacturers.
d. Inadequate Special Process Specification: The PAH forging specification was determined to be insufficient and lacked the necessary detail to adequately control forging temperatures. Inadequate process specificity can lead to variations in supplier process methods and procedures that can have significant effects on the service life of critical reciprocating engine parts.
e. Crankshaft Fatigue Life: The crankshaft has a sufficient design margin between operating stresses and material endurance limit to result in an effectively infinite service life for defect-free material when installed in either the TIO-540 or IO-540 engines. The geometry and materials specified in the crankshaft design definition are adequate for the current operating loads.

f. Propagation of Flaws: Crankshaft operating loads are sufficient to propagate typical flaws associated with the honeycomb feature.
g. Detectable Flaws: The subsurface threshold flaw size that can propagate under normal operational loads is too small to be detected with current NDI techniques.
h. Damaging Cycle Accumulation: TIO engine models accumulate damaging stress cycles at a much faster rate than IO engine models. Crankshafts with honeycomb features installed in TIO engines will most likely fail prior to the TBO of the engine, whereas crankshafts with honeycomb features installed in IO engine models could operate past TBO.
i. 150 Hour Endurance Test: The test profile of the 150 hour endurance test is results in the accumulation of a sufficient number of crankshaft damaging stress cycles to propagate the 95% flaw. However, the 150 hour endurance test results in the accumulation of only 8 million stress cycles at max power, which is less than the 10 million max stress cycles associated with infinite fatigue life.
j. Honeycomb Feature: The honeycomb feature was caused by overheating the billet at Interstate prior to forging.
k. Charpy Test: The Charpy test is a reliable method of verifying that the temperature of the forging was not exceeded. It is imperative that the samples be removed from forgings in areas where the material was in tension during the forging process. The present location where Charpy specimens are removed from the forging prolong appears to be acceptable based on correlations with specimens removed from the critical area.
l. Vanadium: Vanadium addition to the steel was successful in eliminating distortion, but may have reduced the margin between the maximum allowable forging temperature and the temperature at which the honeycomb feature would form.

Key Recommendations

Key "Recommendations" are related directly to the root cause of the crankshaft service problem:

a. FAA Regulations and Policy Relating to Oversight of Critical Processes: FAA regulations and policy relating to oversight of critical processes performed at either a supplier, or at the PAH, should be strengthened to require surveillance on critical part process suppliers. The failures stems from a lack of adequate supplier control by the PAH, failing to ensure the critical process supplier had adequate controls over the maximum forging temperature.
b. FAA Regulations and Policy Relating to Validation of Critical Processes: FAA regulations and policy relating to validation of critical processes performed at either a supplier, or at the PAH, should be strengthened to require

formalized Critical Manufacturing Process Validation (CMPV) systems. The CMPV system should be integrated into the initial certification process and design change control system to track to ensure FAA ACO oversight of new and/or changed processes.

c. Subsurface Flaw Inspection: Flaws of the threshold size are not detectable with conventional NDI technology. Therefore, screening of crankshafts and crankshaft material during production for indicators of existing flaws (such as honeycomb), and controlling material properties during manufacture is necessary to prevent in-service crankshaft failures.
d. Crankshafts Installed in IO Engines: A service program should be developed for crankshafts installed in IO engines that either screens the crankshafts for honeycomb or retires the crankshafts from service to minimize the probability of in-service failures.
e. Substantiation of Crankshaft Major Material, Process or Supplier Changes: Durability testing beyond the 150 hour endurance test should be performed to accumulate more than 10 million cycles at max power for qualification of major changes to crankshaft material, processes, or suppliers.
f. Classification of Major/Minor Design Changes: The FAA should review current design change classification procedures at reciprocating engine and parts manufacturers and standardize those procedures to ensure changes in critical parts and processes are adequately substantiated.
g. Charpy Test: The Charpy test, or other equivalent means, should be an integral element of statistical process control procedures for steel forging process. This should be done for all critical fatigue loaded steel parts in reciprocating engines.
h. Process Control: Process control is essential at the vendor to make sure that the forging temperatures are not exceeded.
i. New Alloys: The specification of a new alloy in a critical part design should be classified as a major design change.

Other Lessons Learned

Other "Lessons Learned" are not directly related to the root cause of the crankshaft service problem:

a. TBO Substantiation: Certification compliance programs for derivative reciprocating engine models of increased power do not typically re-validate the TBO in accordance with FAR 33.19. Performance of the 150 endurance test is insufficient to validate TBO's beyond 600 to 800 hours, so additional testing should be performed, or manufacturer to implement a "lead the fleet" program to determine/increase TBO.

b. FAR 33.43 Bending Stresses: Compliance with FAR 33.43 does not typically address the effect of bending stresses on crankshaft fatigue life. Bending stresses are assumed to be proportional to engine power, and therefore it is assumed that the time at max power during the endurance test is sufficient to validate an acceptable material endurance limit.
c. Fleet Operator Procedures: Fleet operators of reciprocating engine-powered General Aviation airplanes typically use conservative operating procedures relative to detonation margin.
d. Lean of Peak Operation: Lean of Peak operation can lead to inadvertent detonation if the airplane is equipped with inadequate engine instrumentation, or if the aircraft/instrumentation is not in accordance with manufacturers requirements, and/or the pilot does not make mixture adjustments when the engine power or ambient conditions change.
e. Material Inclusions: Inclusions exist in the material that are consistent with quality levels required in VAR melted steel per AMS 6414.

Other Recommendations

Other “Recommendations” are not directly related to the root cause of the crankshaft service problem:

a. Durability/TBO Substantiation Guidance: ANE should publish policy and/or guidance describing durability and TBO substantiation compliance methods for new and derivative reciprocating engines.
b. Vibration Testing Guidance: ANE should publish policy and/or guidance addressing substantiation compliance methods for vibration testing under 33.43. In particular, this policy should address bending stresses.
c. LOP Informational Bulletin: ANE should work with ACE to publish an informational bulletin or article advising of the risks of LOP operation.
d. Engine Management: ANE should work with Flight Standards regarding the development of educational programs for pilots about topics such as fuel mixture management, turbocharger operating procedures and engine maintenance issues in GA aircraft that may be included during recurrent training seminars and the Wings program.

1. INTRODUCTION

a. Background

Between March, 2000 and August 2002, 17 failures of crankshafts installed in Textron Lycoming TIO-540 series engines occurred. One of these events resulted in a serious accident and an associated NTSB investigation. In response to this problem, the FAA issued two emergency Airworthiness Directives (AD's) and one Immediate Adopted Rule AD mandating replacement or inspection of suspect crankshafts.

In the course of conducting the investigation and developing the initial corrective action for this service problem, many questions were generated in regard to the failure mode cause and in regard to the design and certification process used to approve the crankshaft. Consequently, the Engine and Propeller Directorate determined that it was necessary to conduct a formal investigation of the failure mode and a formal evaluation of the methodology and procedures employed for the design and certification of these crankshafts. To accomplish this, the Lycoming Crankshaft Special Certification Review Team (SCRT) was formed.

The SCRT charter that was established by the Directorate directed the team to further investigate the recent unsafe condition associated with Textron Lycoming TIO-540 and LTIO-540 engine model crankshafts to determine the root cause relative to design, manufacture, certification, and operating environment.

The Engine and Propeller Directorate requested the following team members shown in Table 1-1.

TABLE 1-1

Name	Function/Expertise	Organization
Mark Rumizen	Team Leader	Engine & Propeller Standards Staff, ANE-110
Rocco Viselli	Lycoming Engines	New York ACO, ANE-171
Ron Naylor	Lycoming Manufacturing	New Cumberland MIDO-44
Dave Swartz	Metallurgy	Anchorage ACO, ACE-115N
Kevin Brane	Piper Aircraft/Propulsion	Atlanta ACO, ACE-117A
Paul Pendleton	Cessna Aircraft/Propulsion	Wichita ACO, ACE-118WP
Jon Hjelm	Stress/Fatigue Analysis	ANE-171

The team was later expanded with the addition of Chip Queitszch, FAA Chief Scientist and Technical Advisor (CSTA) for engine dynamics, who provided

additional expertise in dynamics analysis and testing to support the fatigue analysis.
One of the initial actions of the team was to organize into four working groups to parallel the long-term Lycoming activities:

TABLE 1-2

Working Group	Members	Responsibilty
Stress Analysis Group	Jon Hjelm Dave Swartz Chip Queitszch	Oversight of Lycoming stress/fatigue/damage tolerance analyses and supporting engine tests
Metallurgical Investigation Group	Dave Swartz Jon Hjelm	Oversight of Lycoming investigation of the honeycomb metallurgical feature
Installation/Operations Group	Kevin Brane Paul Pendleton	Evaluation of the installation design and operating procedures/methods of applicable airplanes
Crankshaft Design/Certification Group	Mark Rumizen Ron Naylor Rocco Viselli	Review crankshaft design and certification data relative to FAA regulations and industry practice.

The team also established a Lotus Quick Place internet site to accommodate the frequent communications between the working group members and the corresponding Lycoming personnel. This internet site provided visibility of the team's activities to Directorate management.

b. <u>SCRT Plan Overview</u>

The SCRT's approach to accomplishing the assigned charter first considered the role of the SCRT in the FAA Aircraft Certification Service Safety Continuum (see Figure 1-1). A plan was then developed in accordance with this role to accomplish the team's objectives (see Figure 1-2). Each of the four working groups developed a portfolio of tasks to investigate the root cause of the crankshaft service problem. The working groups and their associated tasks were structured to focus on areas of the FAA regulations that were related to the design and certification of the crankshaft. The data and information produced from the tasks were used to generate "lessons learned". The relevant elements of the FAA regulations and policy were then evaluated to develop recommendations for improvement.

The format of this report will follow this plan with each working group chapter having a separate section for key tasks, lessons learned, and recommendations.

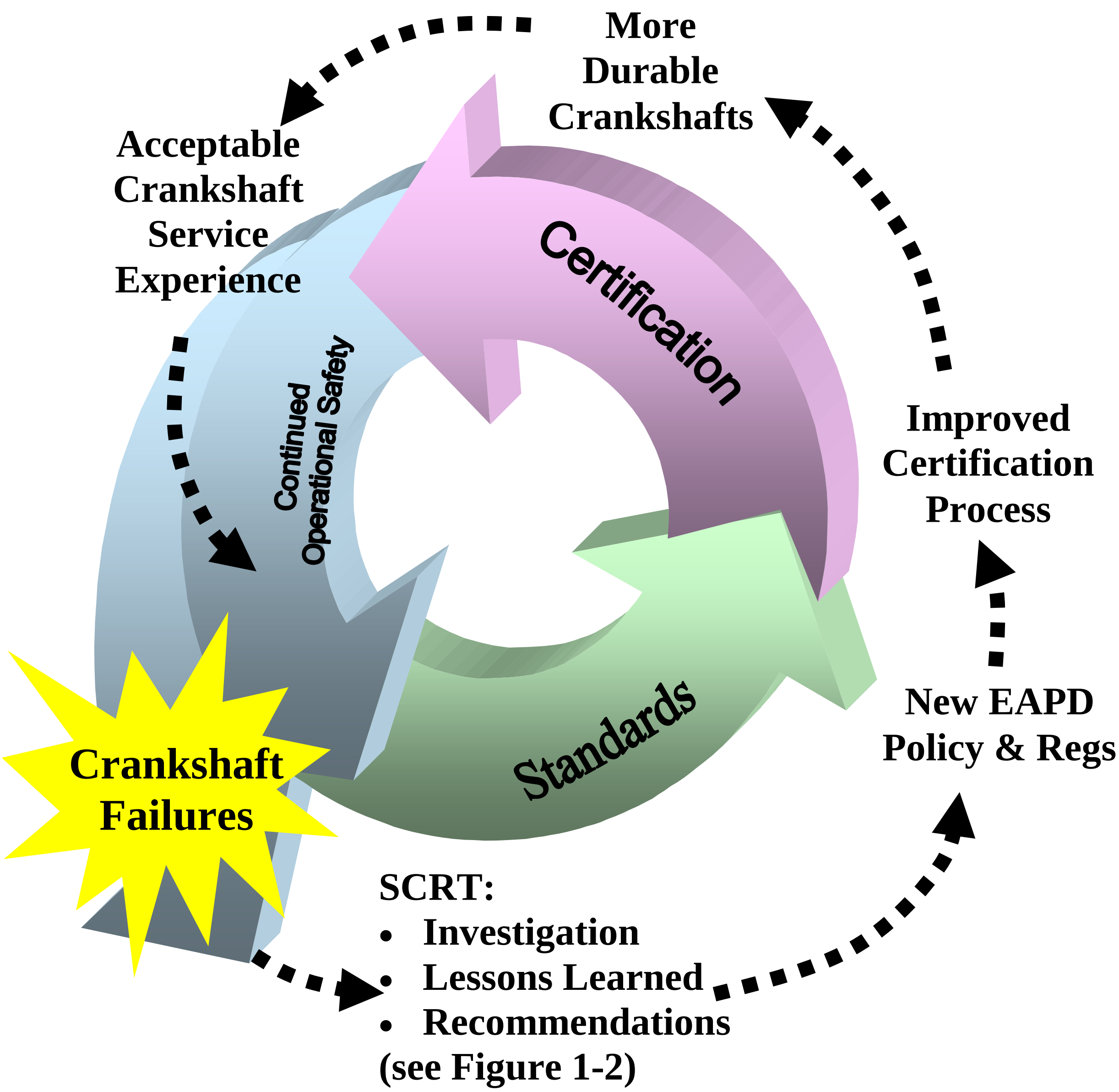


Figure 1-1
SCRT Role in Safety Continuum

Investigation

Chapter 4 — **Design/Certification Working Group**

Key Tasks:
- Review Design History
- Review TC data
- Review ECO's
- Review Process Specs

Chapter 5 — **Installation/ Operations Working Group**

Key Tasks:
- Piper Review
- Cessna Review
- Survey Operators

Chapter 6 — **Stress Analysis Working Group**

Key Tasks:
- Engine & Component Testing and Analysis
- Fatigue Life Analysis
- Fracture Mechanics Analysis

Chapter 7 — **Metallurgical Working Group**

Key Tasks:
- Lyc & SCRT Microstructure Eval.
- Honeycomb Feature Simulation

Lessons Learned (Partial List)

- Crankshaft Fatigue Life
- Material Flaws
- Supplier Oversight
- Critical Processes
- Honeycomb Feature
- Charpy Tests
- Vanadium

Recommendations (Partial List)

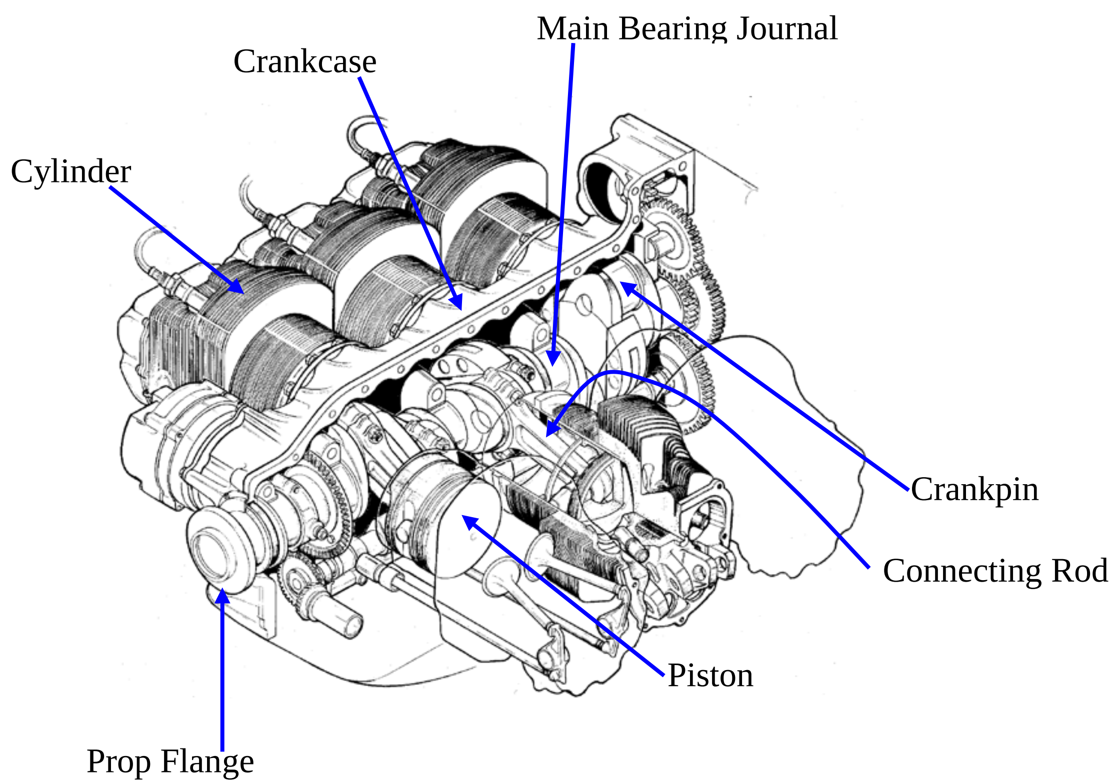
- Crankshaft Service Life
- Crankshaft Inspection
- Oversight of Critical Processes
- Validation of Critical Processes
- Classification of Design Changes
- Process Control
- New Alloys

Figure 1-2
SCRT Plan Overview

2. CRANKSHAFT DESCRIPTION

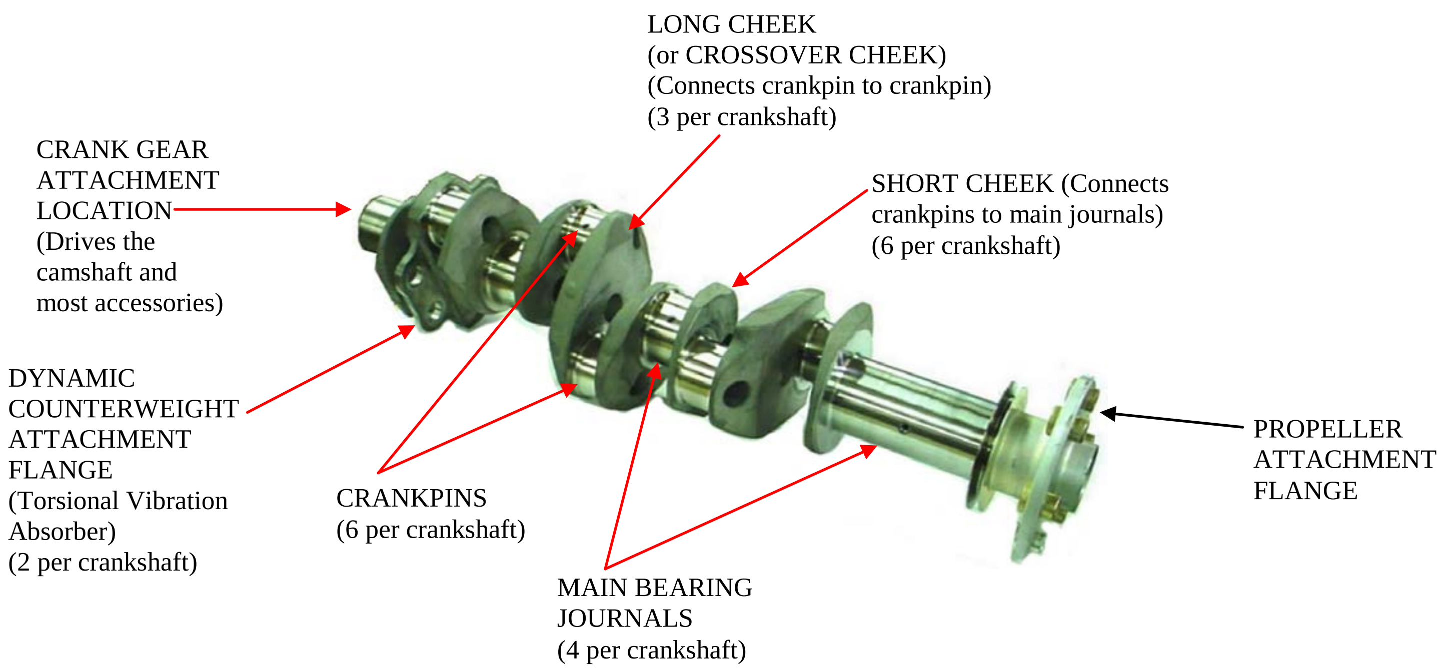
a. Design Overview

An aircraft engine crankshaft converts the reciprocating (back and forth) motion of the pistons into the rotating motion required to drive a propeller. The combustion process in each cylinder drives the pistons in the back and forth motion. Each piston is linked to the crankshaft by a connecting rod. The crankshaft has a bearing surface, called a crankpin, for each connecting rod to attach to. The crankshaft is supported in the crankcase at four positions that are known as the main bearing journals. The main bearings are clamped in place between the crankshaft journals and the crankcase surface. The propeller is bolted to the front end of the crankshaft. The propeller flange and main bearings are located along the axis of the crankshaft, while each crankpin is offset to accommodate the reciprocating motion of the piston and connecting rod. A representative aircraft reciprocating engine is shown in Figure 2-1.



Representative Aircraft Reciprocating Engine
Figure 2-1

The Lycoming TIO-540 crankshaft consists of six crankpin journals, four main journals and an integral flange to which the propeller is attached. Each of the crankpins has a bearing surface that is subjected to piston combustion loads through a connecting rod. Two dynamic counterweights that are located on the rear long cheek of the crankshaft control torsional vibration and hence control torsional (or twisting) stresses. A gear at the rear of the shaft drives the camshaft and most accessories. These features are depicted in Figure 2-2.



Crankshaft Features
Figure 2-2

The crankshaft is subjected to the combustion forces applied by the pistons. In a Lycoming TIO-540 engine, the maximum combustion force (at maximum rated power) is about 18,000 lb. per piston, and this force not only causes the crankshaft to twist, but also causes it to bend. This then produces twisting and bending stresses in the crankshaft. There are other forces, but for a TIO-540 they are relatively small: the combustion force is by far the biggest. In a four-stroke engine such as the TIO-540, the combustion event for each cylinder occurs only every second revolution of the crankshaft. The imposition of bending stresses on the crankpin coincides with this cyclic combustion force.

Consequently, each crankpin experiences a full bending stress cycle every two revolutions of the crankshaft.

Bending stresses are far greater than torsional (twisting) stresses and safety factors in torsion are greater than those in bending. Therefore, an overstressed crankshaft is more likely to fail in bending than in torsion. One of the reasons that the torsional stresses are lower is the presence of the counterweights (torsional vibration absorbers) which keep the torsional levels within controlled limits. The bending stresses, which are greatest in the fillets (the transition from the crankpin bearing journal surface to the long cheek), are primarily dependent on combustion pressures and cannot be mitigated.

b. Manufacturing Overview

The crankshaft is forged into shape from high purity steel. After final machining to the drawing dimensions, a surface treatment called “nitriding” is applied to provide high fatigue strength and wear resistance. A general overview of the Lycoming crankshaft manufacturing process is described below and shown in Figure 2-3. A more detailed review of specific manufacturing process steps and the influence on material properties is discussed in the Metallurgy section (Chapter 7).

1. Steel to specification AMS 6414 (also commonly referred to as **V**acuum **A**rc **R**emelt SAE 4340) is melted in an electric arc vacuum furnace and formed into large ingots at the steel mill. The ingots are reduced by rolling at high temperature into bars that are several feet long. They are then shipped to Citation Interstate Forge for further processing.

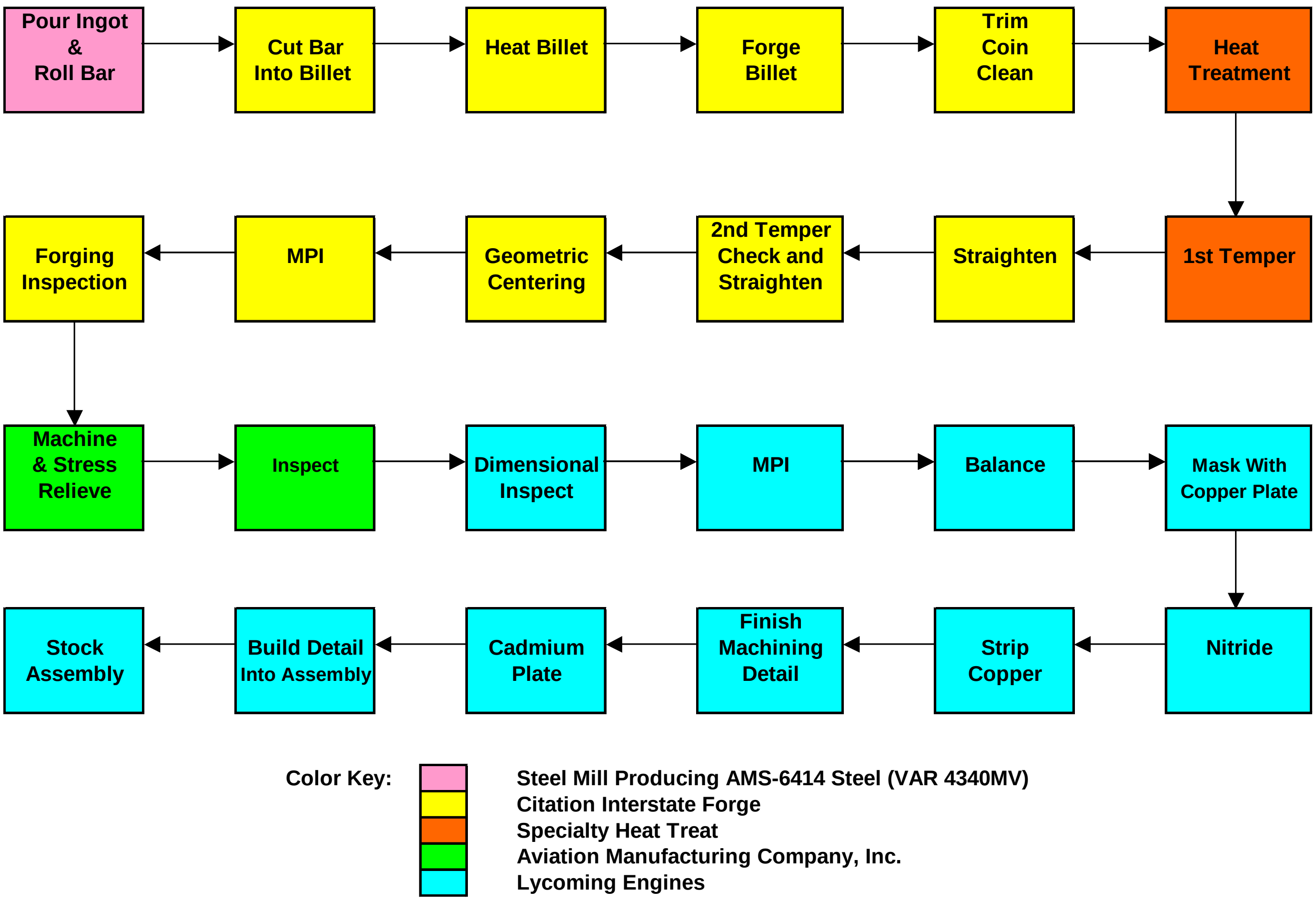
2. The forge shop cuts the bars into shorter pieces (billets) that are suitable for being inserted into the crankshaft forging dies.

3. Each billet is heated to the required forging temperature (2250°F +/- 100°F), placed in the forging die, then struck (hammer forged) or pressed (press forged) to form the raw crankshaft forging. The scale (oxide coating) and steel flash are then removed from the forgings by blasting and grinding.

4. The cleaned forgings are then shipped to Specialty Heat Treat for heat treatment (normalizing, austenitizing and tempering), which refines the steel microstructure, reduces the hardness and increases the ductility.

5. The heat-treated forgings are then shipped back to Citation Interstate Forge where they are straightened, tempered for a second time and straightened again (if necessary). Centering holes are then drilled in each end of the

forgings, followed by Magnetic Particle Inspection (looking for cracks and surface flaws) and general dimensional checks.



Crankshaft Manufacturing Process
Figure 2-3

6. The forgings are then shipped to the Aviation Manufacturing Company for machining, stress relieving and further inspections, before being forwarded to Lycoming for final operations.

7. At Lycoming, the machined forgings are dimensionally inspected, subjected to another Magnetic Particle Inspection, and mass balanced in a rotating machine.

8. Preparation for nitriding is then begun by copper plating those areas that do not require nitriding. Each crankshaft is nitrided for several hours at about

980°F in an atmosphere of dissociated ammonia. The copper is then stripped from the masked areas.

9. Finish machining is then conducted before cadmium plate is applied to those areas exposed to atmospheric corrosion. The main and crankpin journals are polished.

10. Finally, each shaft is assembled with bushings, oil transfer tubes and counterweights, as required.

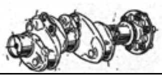
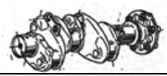
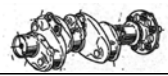
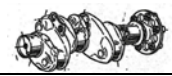
c. Lycoming Crankshaft Applications and History

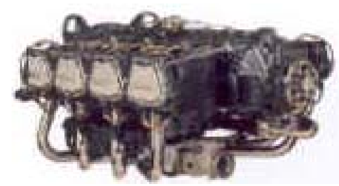
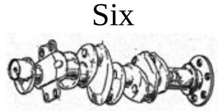
1. Crankshaft Applications

Lycoming produces 7 different crankshaft forgings for its engines as summarized in Figure 2-4. These seven forgings undergo final machining and the assembly of attaching hardware to result in many different final crankshaft configurations. The P/N 27000 and 27101 forgings do not incorporate provisions for counterweights and are designed for lower horsepower engines with fixed-pitch propellers. The 17000 P/N series crankshaft forgings are all designed to accommodate counterweights to mitigate the higher torsional stresses that the higher horsepower engines produce.

Figure 2-4 reflects the forging suppliers and processes in effect at the end of year 2001. Since that time, Lycoming has been working with the forging supplier, Interstate, to transition to a press forge process for all crankshafts. In the future, it is very likely that Lycoming will transfer all crankshaft forging production to an alternate supplier.

The P/N F13F17707 forging is used for the higher horsepower TIO-540 six cylinder engines and is the focus of the SCRT investigation. It is highlighted in Figure 2-5 to reflect this. In the next section of this report, a detailed summary of the engine and airplane applications of this specific crankshaft forging is provided along with a history of the forging design.

Engine Series	-320 	-360 	-360 (Controllable Prop) 	-360 (Turbocharged) 
Cylinders	Four 	Four 	Four 	Four 
Horsepower	150-160	180	180-200	210
Forging P/N	27000	27101	17202	17303
Forging Supplier	Interstate	Interstate	Interstate	Krup-Gerlach (not currently being produced)
Forging Process	Press	Press	Hammer	Press
Typical Airplanes	Cessna Skyhawk Piper Warrier	Cessna 172 Piper Archer	Piper Arrow Mooney 201	Commander 112 Enstrom (Helicopter)

Engine Series	-540 (small main bearing) 	-540 (large main bearing) 	-720 
Cylinders	Six 	Six 	Eight 
Horsepower	230-270	290-350	400
Forging P/N	17606	17707	17808
Forging Supplier	Interstate	Interstate	Interstate
Forging Process	Hammer	Hammer	Hammer
Tyical Airplanes	Cessna 182 Robinson R44	Cessna T206 Piper Saratoga	Comanche RAM STC's

Lycoming Crankshaft Family
Figure 2-4

2. <u>TIO-540 Large Main Bearing Crankshaft Family</u>

Figure 2-5 shows the progression of the P/N F13F17707 forging from the one forging blank to the many finished crankshaft configurations that are installed in Lycoming engines.

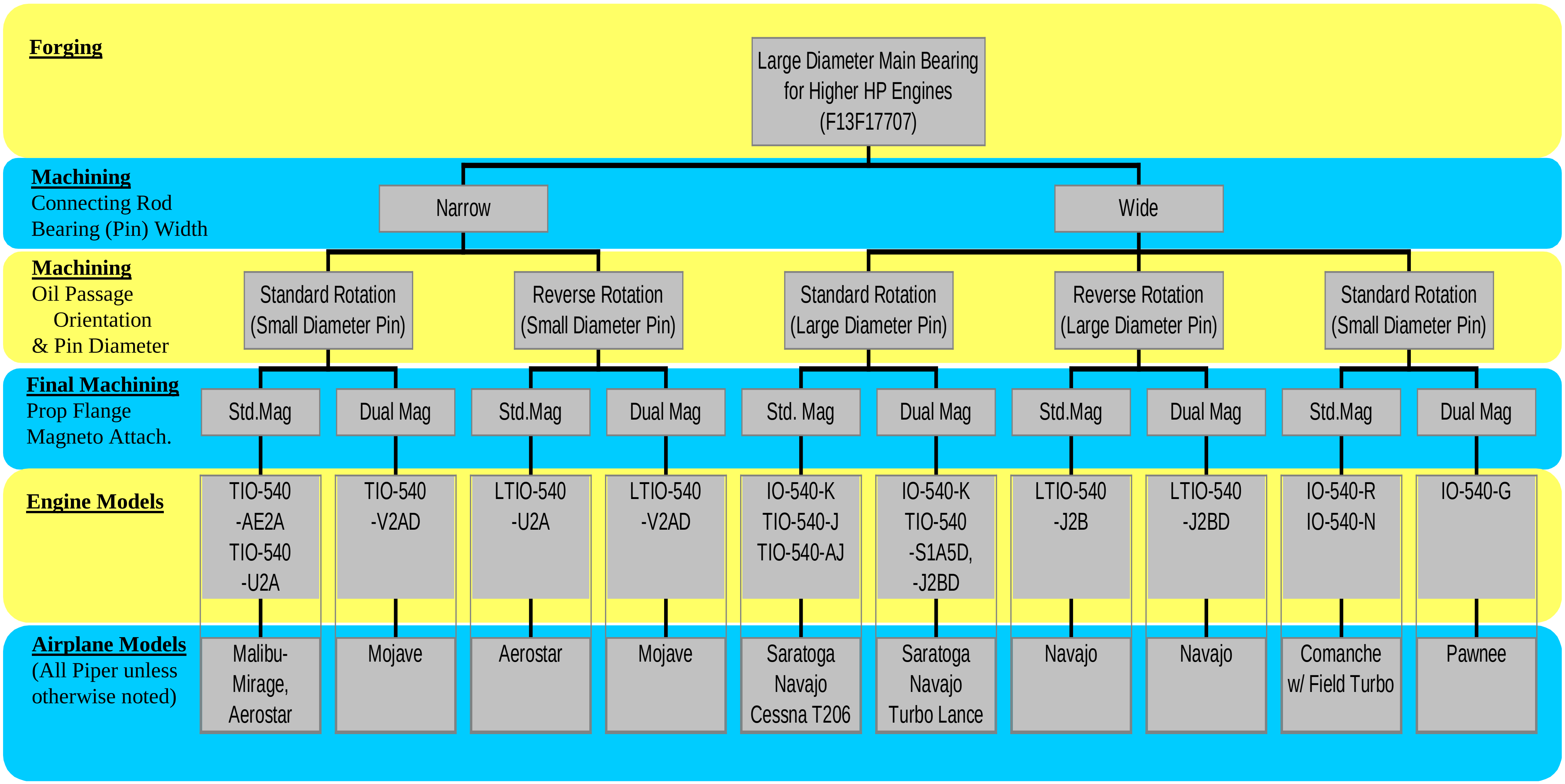
The forging blank is machined to at the crankpin journal to produce a specific crankpin width (narrow or wide) and a specific crankpin diameter (small or large).

The main bearing journals are also machined to the same final dimensions for all engine model configurations that use the P/N F13F17707 crankshaft forging.

Other machined features include the prop flange configuration, to accommodate different types of propellers, and the oil passage orientation, which is dependent on the intended direction of rotation of the crankshaft when installed in the engine.

Attaching hardware will also define the final configuration of the crankshaft. Different magneto drive gears are required depending on whether the engine is equipped with two magnetos, or with a one “dual” magneto. Engines intended for use with a fixed-pitch prop require the installation of the oil plug at the forward end of the crankshaft, whereas adjustable-pitch props do not use the oil plug.

The counterweights and attaching hardware are common to all engine models.



TIO-540 Large Main Bearing Crankshaft Applications
Figure 2-5

3. TIO-540 Large Main Bearing Crankshaft Forging Design History

Figure 2-6 provides an overview of the P/N F13F17707 forging design history and the production rate of that forging. The following is a discussion of the information provided in that chart.

The TIO-540 large main bearing crankshaft was first certified at 310 HP in the TIO-540-A1A engine December 6, 1965. This original forging, part number 75291, was produced with counterweight pads on the 3-4 and 5-6 crossover checks. Machining was required to remove the pads on the 3-4 crossover checks for the final configuration crankshaft.

In 1966, an engineering change was processed to eliminate the counterweight pads from the 3-4 crossover cheeks, thus eliminating a machining step from the manufacturing process. The new forging (part number P/N 76761) only had counterweight pads on the 5-6 crossover checks.

Over the next decade, several new engine models with increased horsepower ratings were certificated with crankshafts made from the P/N 17707 forging:

- The (L)TIO-540-F2BD at 325 HP in 1972
- The (L)TIO-540-J2BD at 350 HP also in 1972
- The TIO-R2AD at 350 HP in 1975

In 1978, ECO 20716 was processed to change the steel material from air melt steel (AMS6415) to vacuum arc remelt steel (VAR) (AMS6414). The forging P/N was changed from 76761 to FLW-17707. This change was incorporated as corrective action for service problems with air melt shafts. These shafts were cracking due to subsurface inclusions introduced during the air melt process. The VAR process produces cleaner steel that is less likely to have subsurface inclusions.

Several additional engine models were certificated at 350 HP using the FLW-17707 forging. These include the following:

- The TIO-540-U2A in 1982
- The TIO-540-V2AD in 1983.
- The TIO-540-W2A in 1984.

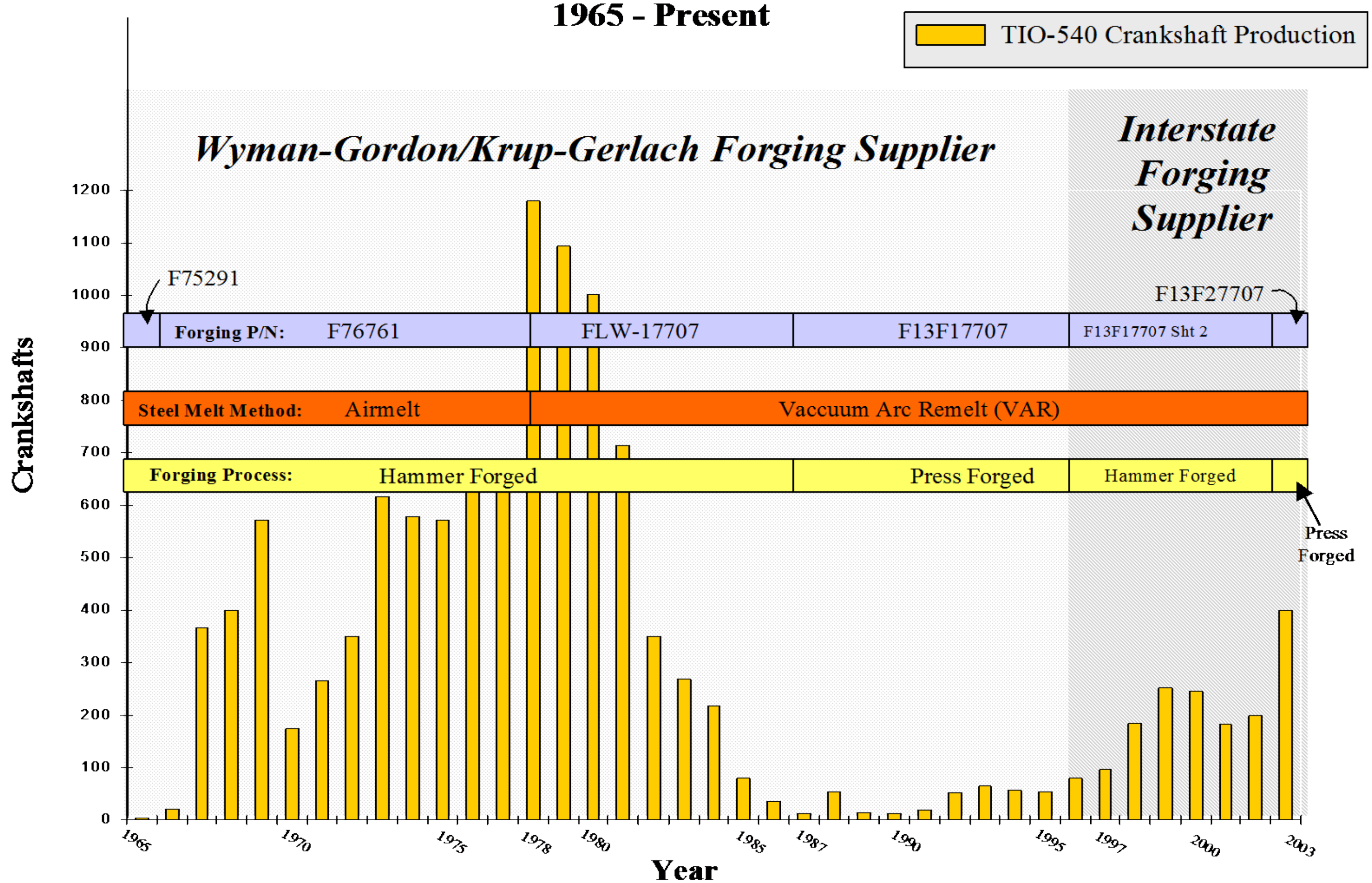
In 1986, ECO 22736 was processed to change the manufacturing process from hammer forging to press forging. Press forging shapes the hot steel at lower strain rates and in a more controlled temperature environment. The forging P/N was changed from FLW-17707 to F13F17707.

The TIO-540-AE2A engine model was certificated at 350 HP in 1988 using this latest forging P/N.

In 1996, Krup-Gerlach announced that they would no longer manufacture crankshaft forgings for aircraft engines. Lycoming processed ECO 25139 to replace Krup-Gerlach with Interstate. Coinciding with this supplier change, the forging process was changed from press forging to hammer forging with associated dimensional changes to accommodate Interstate's requirements. This was reflected as a second sheet in the existing drawing rather than a new forging P/N.

In October 2001, ECO 25769-A changed the forging process back to press forging at Interstate in response to the service problem with the large main bearing shaft. The forging P/N was changed to F13F17707 at that time.

Figure 2-6
TIO-540 Large Main Bearing Crankshaft Forging History
1965 - Present

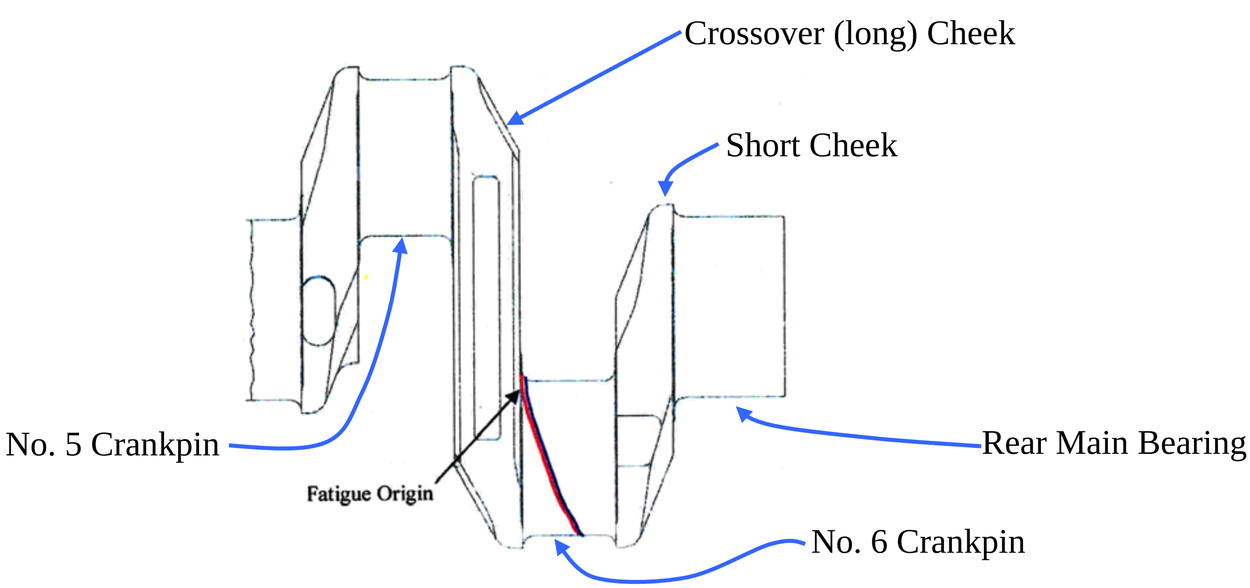


3. CRANKSHAFT SERVICE PROBLEM OVERVIEW

a. <u>Failure Investigation and Identification</u>

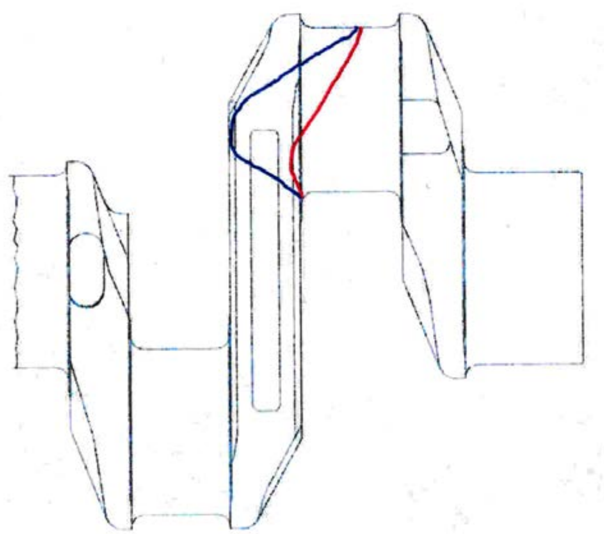
Beginning in 2000, failures of crankshafts in the TIO-540 series turbocharged engines rated at 300 horsepower and higher began occurring. The failures all occurred in the area of the rear cross over cheek between the number five and six crankpin journals, and all were fatigue type in nature from subsurface origins (as observed when the origin was not mechanically damaged). Figures 3-1 through 3-4 graphically depict the location of the crack through the crankshaft geometry.

Location of Crankshaft Cracking
(3-D View of Complete Crankshaft)
Figure 3-1

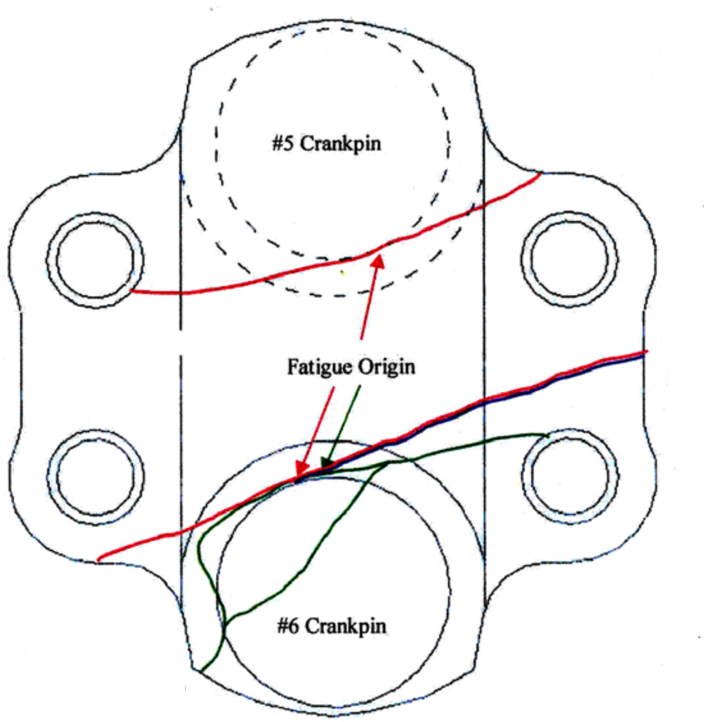


Location of Crankshaft Cracking
(Side View of Crankpin Section)

Figure 3-2



Location of Crankshaft Cracking
(Side View of Crankpin Section)
Figure 3-3



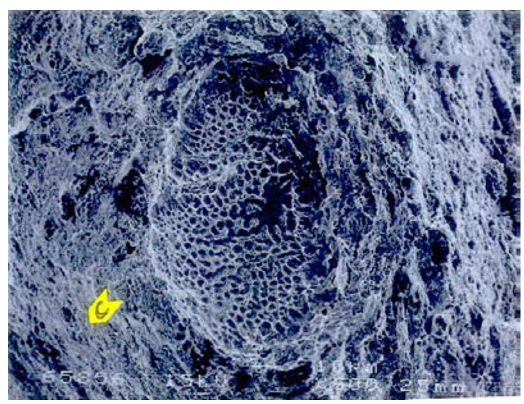
Location of Crankshaft Cracking
(Aft Looking Forward)

Figure 3-4

Lycoming's initial investigation found that the subject broken crankshafts were made from six specific raw material heat codes produced by Republic Steel and forged at Interstate between March and December of 1999. These crankshafts were produced with a hammer forging process after heating in a semi-continuous gas furnace. Examination indicated the failures occurred at the #5 or #6 crankpin in the area of maximum load from peak cylinder firing pressure. The fracture surface indicated a fatigue type failure with the typical beach marks from a subsurface origin, when observable, originating just below the nitride case. Material and dimensional analysis of the shafts found that they conformed to the Engineering drawing requirements and material specifications.

As the crankshafts fractured during engine operation, the parting surfaces experienced an amount of smearing. As a result, only one fracture surface was found to be undamaged at the origin allowing electron microscope examination. This inspection indicated the fracture origin appeared to be a planar, grain like structure approximately .005 X .010 inches in size (as shown in Figure 3-5).

Planar Feature at Crack Initiation Site
Figure 3-5



Honeycomb Feature
Figure 3-6

Charpy impact testing of crankshaft specimens from the suspect material lots revealed "honeycomb" like features that were prominent in distinct areas on the fracture face. Some of these areas were several thousandths on an inch in size. The honeycomb areas appeared as shallow planar features resulting from the Charpy test ductile fracture mode. Lycoming theorized that they were indicative of a prior austenitic grain boundary remaining from high temperature processing. The honeycomb feature is shown in Figure 3-6.

In January 1999, Lycoming modified the crankshaft material specification, AMS 6414, to control the amount of Vanadium between 0.07-0.11%. Lycoming noted that the Vanadium level had varied from 0.01-0.09% over a period of several years. Controlling the Vanadium levels allowed an increase in the tempering temperature without lowering the hardness of the forging. This increase in temperature ensured greater residual stress relief necessary for straightening of crankshafts during the manufacturing process. Lycoming has since changed from gas furnace heating/hammer forging to induction heating/press forging with tighter temperature process controls. This permitted Lycoming return to AMS 6414 material without the increased level of Vanadium and utilize the original tempering temperatures. Lycoming has not identified any metallurgical evidence to date to indicate that the presence of the higher level of Vanadium resulted in the any detrimental condition. However, all broken crankshafts were fabricated from AMS 6414 with Vanadium addition.

Lycoming concluded that the honeycomb feature was a prior austenitic grain boundary resulting from overtemperature of the material during the fabrication process. If the features were of sufficient size and located in areas of high stress, they caused degradation in the material fatigue properties. Lycoming conducted a forging simulation that demonstrated that the prior austenitic grain boundary condition could be produced with forging temperatures exceeding 2450 degrees F. The simulation further showed that adequate temperature control at or below 2350 degrees F during the heating process for the forging billet would eliminate the presence of the grain boundary condition. They concluded that elimination of the honeycomb feature reinstated the previous strength margin to the crankshaft in service operation.

In-depth metallurgical investigation also revealed that the application of working strain from the hammer forging operation to the overtemped forging blank caused the formation of microcracks in the honeycomb features. These microcracks caused a localized reduction in material fatigue strength that lead to the crankshaft failures.

A more in-depth review of the metallurgical issues related to the failure investigation is provided in the metallurgical section (Chapter 7) of this report.

b. Corrective Action Program

Please refer to Figure 3-7 for an overview of the corrective action program.

The initial service failures of the crankshafts began in May 2000. Figure 3-7 shows three events in this time period, but it's important to note that there can be a significant lag between the occurrence of a General Aviation (GA) service event and the receipt of the report by the engine manufacturer. In this case, Lycoming was only investigating one of the initial three events in 2000, and the cause of this event was initially assumed to be a main bearing failure. Corrective action was in place for main bearing failures, so no further action was considered necessary.

As more events began occurring in 2001, Lycoming's investigation shifted from main bearing failures to fatigue overload, thought to be caused by propeller strikes or improper engine operation. Towards the end of 2001, the honeycomb feature was identified in one of the failed shafts. Service problems with Teledyne Continental Motors (TCM) crankshafts two years earlier had prompted Lycoming to examine their shafts for this manufacturing defect. By early 2002, a suspect manufacturing lot had been identified by Lycoming that included crankshaft forgings produced from March 1999 to December 1999. Lycoming's investigation concluded that there must have been a substantial variation in temperature control during the forging operation to cause the formation of honeycomb in these manufacturing lots.

In February 2002, Lycoming issued Service Bulletin 550 and the FAA issued AD 2002-04-51 that recalled crankshaft forgings produced from March 1999 to December 1999. At that time, incidents of broken crankshafts were restricted to that time period. In August, a broken crankshaft occurred outside the initial recall range and prompted SB 552 and AD 2002-17-03. These actions included the crankshafts already replaced under SB 550/AD 2002-04-51 as well as those produced from the end of the initial recall period up to March 2002, when the process changed to press forging and induction heating. Lycoming data also indicated that some significant variation existed in the forging process prior to the date of the original recall. In September 2002, Lycoming issued SB 553 and the FAA issued AD 2002-19-03 that required an inspection of the crankshafts manufactured by Interstate prior to March 1999. The inspection entailed the drilling of a small specimen from the propeller flange and sending this specimen to a Lycoming laboratory for a Charpy test and examination for honeycomb. Evidence of honeycomb was discovered in approximately 30% of these shafts.

The crankshaft forging has been changed to a press forged process with more rigorous control of forging temperature. In addition, a prolong has been added to the crankshaft forging design. The prolong is removed from completed crankshaft forgings and undergoes a Charpy examination for evidence of honeycomb. No honeycomb has been found in these new production crankshafts.

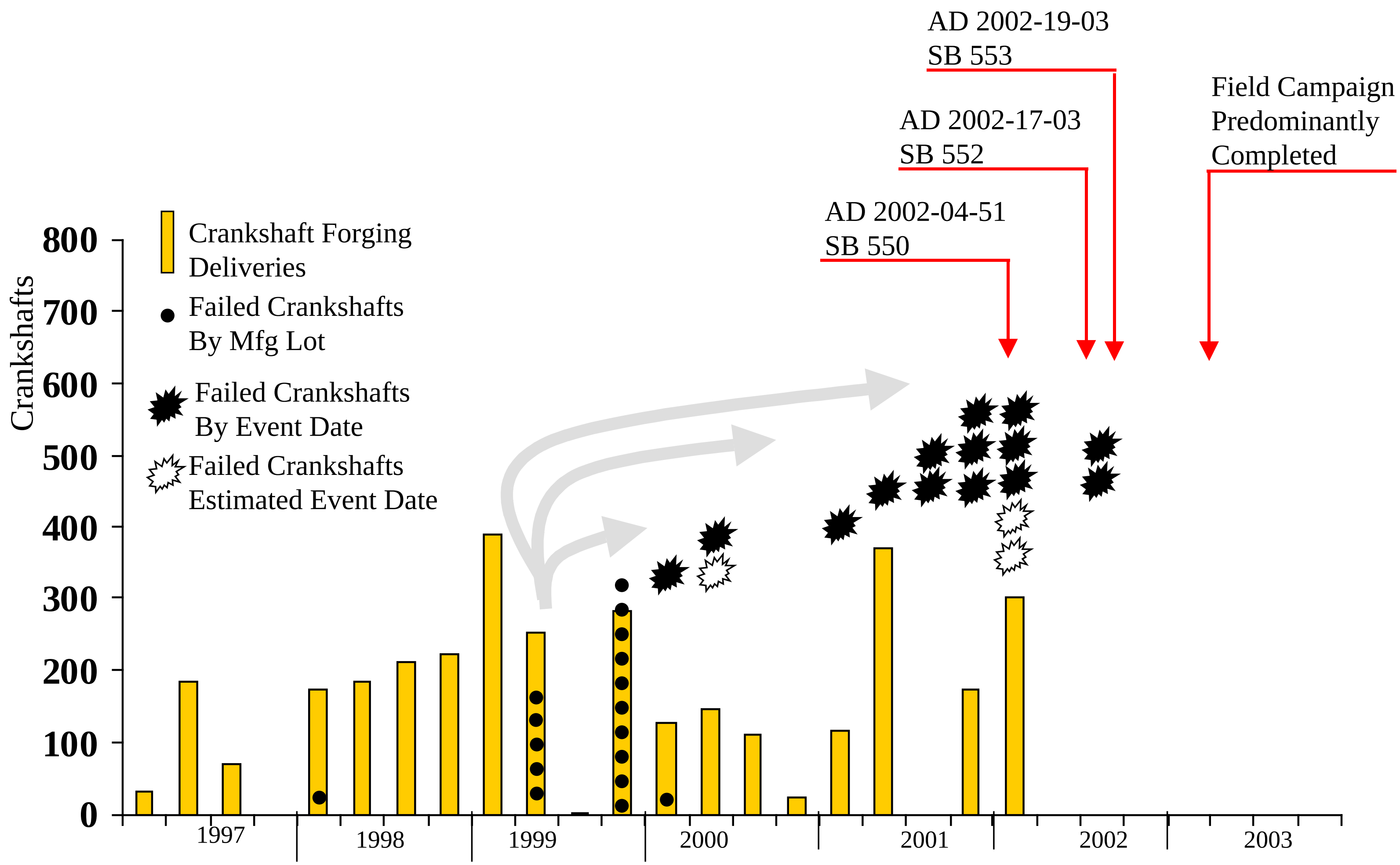


Figure 3-7
Overview of Corrective Action Program

4. DESIGN/CERTIFICATION WORKING GROUP

INVESTIGATION

The Special Certification Review Team (SCRT) Design/Certification Working Group was tasked with evaluating past and current design and certification processes at Textron Lycoming. To accomplish this, the group reviewed the certification process for the first Textron Lycoming TIO-540 engine, approved in 1965, and compared it to the present day type certification process. The group's efforts were directed at determining whether the old process was robust enough as compared to today's certification process requirements. The working group also evaluated the engineering design change and manufacturing process changes as applied to TIO-540 engine model crankshafts over the years to better understand the suitability of these other key elements of the design and certification process. A summary of documents reviewed for this task is shown in Appendix 1.

a. Engine Type Certification

Overview: The TIO-540-A1A was the first turbocharged *fuel injected* 540 engine model. Because of the higher (310 horsepower) rating achieved with this engine model as compared to earlier versions of the –540, it was the first equipped with "large main bearing" crankshaft configuration (see Chapter 2) that is the focus of this report. Other turbocharged versions of different engine models preceded the TIO–540-A1A, such as the TVO-435 and TVO-540, but they were not fuel injected and were rated at lower power levels.

i. Compliance Overview: The TIO-540-A1A was type certificated on December 6, 1965, to the Civil Air Regulation (CAR) Part 13 dated June 15, 1956, Amendment 1, 2 and 3, effective date October 1, 1959. This preceded the issuance of Federal Aviation Regulation (FAR) 33 which occurred on February 1, 1965. The certification compliance program was done in accordance with Test Inspection Authorization (TIA) No. CE982EA-D. The certification basis was CAR 13 effective June 15, 1956, Amendments 1,2 and 3. The compliance program included pre-test conformity, performance test, torsional tests with two different propellers, and two 150-hour endurance tests (see Appendix 1 for list of reports).

In the review of the 150 Hour Endurance Test report, it was determined that the test requirements of CAR 13.154 that were in effect at the time of this certification program did not require altitude testing of turbocharged engines. However, the approved Lycoming test program imposed more rigorous requirements than the applicable CAR by incorporating simulated altitude testing. The altitude conditions were simulated by throttling the compressor inlet to the desired pressure altitude and applying a vacuum equal to the desired pressure altitude to the turbine outlet.

The vibrational testing focused on the torsional response of the propeller flange to the installed propeller. However, CAR 13.151 specifically requires evaluation of bending stresses along with torsional stresses. No evidence of bending stress evaluation was found during a review of the certification data.

ii. <u>Conformity:</u> The Manufacturing Inspection Section Representative conducted a conformity check of the test engine in accordance with the parts list submitted by the Lycoming and also participated in the after test (teardown) inspections of the engine and components. FORM FAA-283 part 1 was completed as part of the TIA conformity. Lycoming provided the FAA Form 317. The tests outlined in the TIA were either witnessed by personnel from EA-214 or authenticated by the DEER at Lycoming. It is not apparent from the review of the certification reports that process conformity was performed on the featured engine components and parts.

iii. <u>Engine Type Certification Summary:</u>

As stated above, CAR 13.154 and the early versions of FAR 33.49 did not require altitude testing of turbocharged engines. In 1974, amendment 33-6 incorporated altitude testing of turbocharged engines in FAR 33.49. The incorporation of this change resulted from industry practices deemed necessary by the engine designers, such as Lycoming, to fully evaluate the durability of turbocharged reciprocating engines. In the case of the TIO-540-A1A engine model, the endurance test profile was consistent with today's requirements and found to be adequate to substantiate the durability of that engine model.

Subsequent derivatives of the turbocharged TIO–540 engine models were developed and certified over the next several decades at higher horsepower ratings, culminating in the 350 HP TIO-540-AE2A The certification program for each new model typically consisted of a 150 hour endurance test and a torsional vibration test.

Measurement of only torsional stresses when complying with CAR 13.150 or the FAR 33 equivalent (33.43) appears to be typical of reciprocating engine certification programs. Based on prior analyses and bench component tests, peak bending stresses are assumed to occur at maximum rated power for all engines and crankshaft designs. Therefore, it is implied that it is not necessary to "measure" the bending stresses to evaluate them, but rather only necessary to operate at the most severe loading condition for the required 10 million cycles. This is accomplished during the 150 endurance test.

b. Major/Minor Design Changes

i. Overview: The Design/Certification Working Group reviewed 22 crankshaft design change projects to evaluate the scope of substantiation performed for each. Those design changes that were incorporated into the type design were implemented via Engineering Change Orders (ECO's). Of the 22 projects evaluated, 21 were issued as ECO's (see Table 4-1).

ii. Classification of Design Changes: Investigation revealed that up until recently, Lycoming did not classify ECO's as Major /Minor, but rather used an internal classification scheme that reflected production priorities rather than safety priorities. As a result, design changes that would have been designated as major were not evaluated against the applicable airworthiness standards and reviewed by the FAA or FAA designees. A review of the design changes listed in Table 4-1 revealed the following:

1. Items 1 through 12 were issued prior to Lycoming's implementation of the Major/Minor classification system. A detailed review of these ECO's revealed that 4 of these should have been classified a major changes (Items 1, 5, 6, 7), and three others could have been classified as major but require additional investigation before a final determination can be made (Items 2, 3, 4). Therefore, only 5 of these twelve ECO's were minor changes, all of the others should have undergone FAA review for compliance with CAR 13.
2. Items 13 through 21 were issued after implementation of the Major/Minor design change classification system. Lycoming had

been authorized by the NY ACO in 1995 to allow DER approval of Major Design Changes, but was still required to submit form 8110-3 with substantiating data. However, there was no evidence to indicate that the DER conducted findings of compliance to FAR Part 33 as would be required by this type of delegation. It is significant to note that Lycoming classified all except item 19 as Minor Changes, but the SCRT review indicated that items 13, 14, and 18 should have also been classified as Major. These three ECO's impacted such critical design characteristics as the forging process and material specification.

3. Lycoming did not classify item 21, but this was a minor change.

Table 4-1
ECO History for (L)/TIO-540 Crankshaft

Item #	ECO No.	Date	P/N	Subject	Lycoming Classification	Brief Explanation
1.	13464	1/10/66	76761	Forging from 75291 to 76761	Priority C	This change removed a second set of forged counterweight ears between number 3 & 4 main bearing. These ears were machined off the 75291 forging.
2.	16753	8/4/71	76763	Increase bearing clearance	Priority C	On long front main bearing (1 & 2) changed from 2.6250-2.6255 to 2.6245-2.6250 Note: Rear main tolerance is 2.6245 – 2.6255
3.	20147	10/19/77	75291	Change hardness callout	Priority C	Changed core hardness range from Rc 32 – 36 to Rc 32 – 37. This change allowed a slightly higher core hardness target and therefore reduced the number of shafts being rejected for low core hardness.
4.	20235	12/22/77	76763	MRB/Cold Straightening	Priority C	Removed requirement to submit to MRB shafts for hot straightening. This ECO did <u>not</u> affect the straightening process.
5.	20596	8/25/78	FLW-17000	Vacuum melt Crankshafts	Priority C	To released new vacuum melt crankshafts for procurement
6.	20716	11/29/78	LW-17726	Vacuum Melt Steel	Priority C	Change from AMS-6415 to AMS –6414 same alloy cleaner version-vacuum remelt. This was done as a result of field history.
7.	22736	11/17/86	F13F17707	Drop forge to Press forge	Priority C	Change from hammer to press forge process.
8.	22791	4/30/87	F13F17707	Facilitate Manufacturing	Priority C	Facilitate Manufacturing.
9.	22879	3/4/88	F13F17707	Clarify Part Requirement	Priority B	Clarify Part Requirement.
10.	23773	1/18/91	F13F17707	Modify Print	?	Vendors request to modify print to agree with current forging practice. (Lycoming did not provide classification of Priority).

Table 4-1
ECO History for (L)/TIO-540 Crankshaft

Item #	ECO No.	Date	P/N	Subject	Lycoming Classification	Brief Explanation
11.	24207	11/23/92	F13F17707	Standardize O-540 crankshafts	Priority B	This ECO Standardizes the O-540 large main counterweight crankshafts.
12.	24309	3/23/93	F13F17707	Facilitate Manufacturing	Priority B	Facilitate Manufacturing. Removed dimension and added dimension for clarification.
13.	25139	7/29/97	F13F17707	Krup to Interstate	Priority B Minor	Change from press forge at Krupp to hammer forge at Interstate.
14.	25352	11/16/98	F13F17707	Increased Vanadium	Priority B Minor	This change specified Vanadium content at .07 - .11 %. Note: AMS 6414 does not specify Vanadium content.
15.	25499	12/14/99	F13F17707	Revise Sheet 2 of Dwg. Showing Interstate Forging configuration	Priority C Minor	Supplier Request (Update Interstate Forging Configuration).
16.	25450-A	1/20/01	F13F17707	Update Drawing	Priority C Minor	Priority Part drawing review /update.
17.	25789	10/23/01	F13F17707	Facilitate Engine Build	Priority C Minor	Facilitate Engine Build.
18.	25769-A	10/23/01	F13F17707	Change Hammer Forged to Press Forged	Priority C Minor	Revised Interstate Forging industries Inc. Hammer Forged Configuration to Pressed Forged Configuration
19.	25803	12/13/01	F13F17707	Return to Standard Material Designation (Vanadium)	Priority B Major	Update LPS-483 Appendix A "Tempering Temp." and change Vanadium content back to the original quantity.

Table 4-1
ECO History for (L)/TIO-540 Crankshaft

Item #	ECO No.	Date	P/N	Subject	Lycoming Classification	Brief Explanation
20.	25850	3/13/02	F13F17707	Facilitate Manufacturing	Priority C Minor	Facilitate Manufacturing.
21.	25850-B	5/16/02	F13F17707	Facilitate Manufacturing	Priority C	Facilitate Manufacturing.
22.	Not Issued	8/18/82	LW-17738	Narrow Pin Crankshaft	Not Classified	Stress survey of narrow pin crankshaft for installation in TIO-540-J2BD engine model

Lycoming Priority Classifications:

Priority A – Improve reliability, correct possible incompatibility with other parts or installation and /or incorporate items mandatory by customer order. This classification will immediately stop production of parts engine build and shipment until changes can be made unless the engineering Change Order dictates a specific effectivity.
Priority B – Correct possible incompatibility and/or undesirable customer reaction. This classification will require the change to be incorporated into the next part produced or the next engine started in Production unless a specific effectivity is dictated by the ECO.
Priority C – Any items not covered by A or B

iii. Substantiation Review: Three of the projects were selected for more in-depth review to assess the extent of Lycoming's technical/engineering evaluation of the proposed changes. Lycoming provided certification reports, metallurgy laboratory inspection data, and other data for the team to review.

1. Vacuum Melt Steel (1978): ECO 20596, Item 5 from Table 4-1, introduced vacuum melt steel to replace airmelt steel in the crankshaft forging. Lycoming performed a material fatigue evaluation of specimens manufactured with the new steel (Ref. Report dated Jan. 22, 1974, "Test of 4340 (AMS 6415) Crankshaft Steel"). This report concluded that the fatigue properties of vacuum melted 4340 were increased by 25% to 50%, relative to air melted material. Lycoming also tested the vacuum melt steel to compare the fatigue strength with different heat treatments and grain flow direction. Lycoming tested 21 specimens, 7 where the steel was air melted and 7 each of two different vacuum melted lots and concluded that the vacuum melt showed higher strength than the air melt. Lycoming also concluded that the longitudinal grain structure showed higher strength that the transverse grain. In addition, Lycoming performed a literature study of the fatigue properties of vacuum melt steel that yielded similar conclusions.

   As stated in Section 2.b.ii.1 above, this change was issued prior to adoption of a Major/Minor classification system. It was designated as a Priority C change, but this only reflected the urgency of production introduction and not related to impact on flight safety.

2. Narrow Pin Crankshaft: Item 22 from Table 4-1. In 1981, Lycoming initiated an ECO project to improve the reliability rate of the TIO-540-J2BD engine crankshaft by incorporation of a strengthened, narrow pin crankshaft. The narrow pin crankshaft is configured with a shorter length connecting rod journal (pin) to allow for thicker cheeks and greater bending strength. At the time, the narrow pin crankshaft was installed in the TIO-540-U2A engine and had demonstrated acceptable service history. Both of these engine models are rated at 350 horsepower and Lycoming believed the narrow pin shaft would improve the reliability of the –J2BD.

   The -U2A engine model, with the narrow pin crankshaft installed, had previously undergone a complete type certification program that included a 150 hour endurance test, crankshaft torsional survey, detonation test and post-test conformity inspection of the tested components. To evaluate installation in the –J2BD engine model, Lycoming performed a stress surveys of both the –U2A and –J2BD crankshafts. These surveys consisted of an instrumented engine test in which actual operating bending stresses were measured in the proximity of the fillet radii of the number 3 and 4 main bearing journals. In addition, a static stress test was performed to enable a comparison between the strength of the two configurations. The data revealed that both configuration crankshafts had adequate safety margins of material fatigue strength relative to the operating stresses, and the –U2A narrow pin configuration offered only a slight improvement in fatigue capability over the –J2BD standard configuration. Lycoming concluded that the recent introduction of vacuum arc remelt steel was adequate for improving reliability of the –J2BD crankshaft and that incorporation of the narrow pin configuration would not provide enough additional margin to warrant issuing an ECO.

3. <u>Krup/Press Forged to Interstate/Hammer Forged:</u> ECO 25139, Item 13 from Table 4-1. This ECO introduced a new manufacturing source and process for the crankshaft forging in 1996. The crankshafts forgings were manufactured by Krup-Gerlach (formerly Wyman-Gordon) from the mid-1960's to the time of this change (1996). Krup-Gerlach used a press forge process to make the forgings during the last several years of production. This ECO introduced a new supplier, Interstate, who used a hammer forge process. This was classified as a minor change by Lycoming, and as such, the forging drawing number was not changed, but rather a second sheet was added to the existing drawing to reflect the Interstate forging configuration. The extent of the substantiation of the ECO consisted of a 1st article conformance report in which all of the drawing dimensions were verified on a sample part, and a Materials Lab examination of a forging to verify material properties such as grain flow, hardness, tensile strength, and cleanliness of the material.

iv. <u>Conformity:</u> No evidence of FAA pre-test or process conformity was revealed during the SCRT review of these major/minor design changes.

v. <u>Major/Minor Design Change Summary:</u> The SCRT review indicated that the technical/engineering evaluation of design changes was adequate until the mid-1990's. At that point, it appears that the evaluation of design changes became less rigorous in the absence of direct FAA oversight. This is best evidenced by the Lycoming evaluation of the change in forging supplier and process from Krup-Gelach to Interstate (paragraph b.iii.3 above). The criticality of this part along with the extent of the change warranted a more comprehensive evaluation that should have included component fatigue and engine testing.

The absence of Lycoming's and FAA's oversight resulted in a diminished emphasis on the FAA airworthiness standards. This contributed to Lycoming's lack of discipline relative to manufacturing process definition and supplier control, and relative to documentation and design control. Compliance with FAA regulations would have necessitated a new part number and drawing for the forging and process conformity of the hammer forging process at the supplier. This would have resulted in a better controlled design along with enhanced Lycoming oversight of the supplier.

However, it's important to note that the design change control system is now functioning properly at Lycoming and major design changes undergo a thorough finding of compliance to FAR Part 33.

c. Manufacturing Process Specification Changes

i. <u>Overview:</u> The SCRT Crankshaft Design/Certification History Working Group selected three (3) Lycoming Process Specifications (LPS's) and their associated Engineering Change Orders (ECO's) for review and evaluation relative to crankshaft manufacturing. The SCRT objective during this review was to determine and understand how Lycoming evaluated process specification changes, and to identify what, if any, metallurgical examination, component/engine testing or analysis was performed to substantiate the process changes.

ii. Lycoming LPS-555 "Crankshaft Balancing Procedure" Revision G dated February 24, 2003 and all subsequent issued ECO's were reviewed and evaluated by the SCRT. Since the initial release of the specification a total of seven (7) ECO's have been issued against LPS-555. All of the ECO's were approved by a FAA-DER and are listed below:

a. ECO 23233 dated 5/17/89 added new forging part numbers and changed LW-17707 to 13F17707.

b. ECO 23757 dated 1/22/91 added new forging outlines.

c. ECO 23959 dated 8/20/91 changed forging part numbers.

d. ECO 25452 dated 7/26/99 changed RPM requirements on all crankshafts from 500rpm to 600rpm, removed paragraph 4 entirely which required "Calibration weights to be inserted in the crankpin lightening holes at the front and rear crankpin locations" and revised 1.41 max to "MAX" (to centerline).

e. ECO 25504 dated 12/16/99 removed metal stamping requirement.

f. ECO 25846 dated 3/7/02 added 4cylinder secondary stock removal cheeks #3 and cheeks #4.

g. ECO 25959 dated 1/27/03 revised/added new forging part numbers.

The SCRT Design/Certification Working Group used the following rationale to select **ECO 25452** for a more in-depth review;

- The ECO release date of August 31, 1999 corresponds with the timeframe of the recent crankshaft failures.
- The process change affected crankshaft forging part number F13F17707.
- Lycoming Engineering identified the ECO as "Major".
- Crankshaft balance can affect the dynamic loading of the shaft during engine operation.

Lycoming Engineering could not provide the SCRT with any documentation, which defined how the process change was substantiated, no analysis, metallurgical examination, or part/engine endurance testing was apparently conducted. According to Lycoming Engineering representatives the change to LPS-555 (via ECO 25452) was initiated as part of a corrective action response to a process audit that resulted in a noncompliance to the specification. During the process audit it was noted that the crankshaft balancing operation RPM exceeded the maximum 500-RPM as defined by the LPS. In addition, the required calibration weights were not being utilized by the operator as required by paragraph four (4) of the LPS. Lycoming Engineering representatives stated verbally the rational for not having substantiating documentation was that the RPM is set by the balance equipment manufacturer and it be adjusted at the specific calibration intervals, the original balance equipment was not changed, and the use of calibration weights were not a requirement for the balancing operation and should have been removed from the specification during a previous revision of the LPS. It appears that Lycoming Engineering simply revised the balancing specification (LPS-555) to fall within the parameters that were observed during the process audit.

iii. Lycoming LPS-468 “Heat Treatment of Steels” Revision U dated February 24, 2003 and all subsequent issued ECO’s were reviewed and evaluated by the SCRT. Since the initial release of the specification a total of thirteen (13) ECO’s have been issued against LPS-468. All of the ECO’s have been approved by a FAA-DER and are listed below:

a. ECO 17795 dated 3/21/73 updated revision levels of specification cover sheet.

b. ECO 18774-dated 1/2/75 for AMS 6440, added temperature and time requirement after quenching.

c. ECO 18853 dated 3/11/75 added sheets 5, 6, 7 for carbon restoration process.

d. ECO 20596 dated 8/25/78 added AMS 6414, changes Anneal, Harden, Stress Relieving.

e. ECO 20864 dated 4/2/79 clarification of decarburization and carburization.

f. ECO 21457-A dated 6/4/81 added heat cycle for AMS 5120, AMS 5122.

g. ECO 22613 dated 2/24/86 complete re-write, removed all instruction sheets, referenced applicable Military Standards for

AMS materials. This change reduced the LPS from 40 sheets to 11 sheets.

h. ECO 23255 dated 6/1/89 complete re-write.

i. ECO 24627 dated 1/3/95 changed furnace temperature uniformity requirements for nitriding on sheet 2, changed method of hardness testing on sheet 7.

j. ECO 24841 dated 2/23/96 changed furnace temperature uniformity requirements for hardening, carburizing, and tempering on sheet 2 to meet industry standards.

k. ECO 25509-C dated 3/29/00 clarified and updated to meet industry standards and current AMS specifications.

l. ECO 25850-A dated 3/11/02 process changes to facilitate supplier (Interstate Forge) manufacturing based on FAA audit findings.

m. ECO 25953 dated 1/17/03 updated process, removed Military Specification MIL-S-851 "Steel Grit, Cut Wire, Iron Grit, and Shot Blast Cleaning and Peening".

The SCRT Design/Certification Working Group used the following rationale to select **ECO 25509-C** for a more in-depth review;

- The ECO release date of April 25, 2000 corresponds with the timeframe of the recent crankshaft failures.
- The process change affected crankshaft forging part number F13F17707.
- Lycoming Engineering identified the ECO as "Major".
- The quench oil temperature was increased, and the oil quench temperature at the beginning and the end of the operation was clarified.
- The quenching process can impact residual stresses and associated fatigue strength of the crankshaft.

Lycoming Engineering could not provide the SCRT with any documentation that defined how the process change was substantiated. Lycoming apparently conducted no analysis, metallurgical examination, or part/engine endurance testing prior to or after this process change. In this case, substantiation was most likely based on the technical knowledge and experience of the company metallurgist.

iv. Lycoming LPS-496 "Stress Relief and Straightening of Crankshafts" Revision E dated August 4, 1999 and all subsequent issued ECO's were reviewed and evaluated by the SCRT. Since the initial release of the specification a total of four (4) ECO's have been issued against LPS-496 "Stress Relief and Straightening of Crankshafts". All of the ECO's have been approved by a FAA-DER and are listed below:

a. ECO 18863 dated 3/14/75 changed "Routing" to "Instruction Sheet".

b. ECO 20830 dated 3/15/79 added the "Straightening of Nitrided Crankshafts" requirements.

c. ECO 21294 dated 9/4/80 added "Room Temp. Stress Relief (Alternate Method)".

d. ECO 25436 dated 6/16/99 reduced time at temperature from 25 hrs. min. to 10 hrs. min.

The SCRT Design/Certification Working Group used the following rationale to select **ECO 25436** for a more in-depth review;

- The June 16, 1999 ECO release date corresponded with the timeframe of the recent crankshaft failures.
- The process change affected crankshaft forging part number F13F17707.
- The time held at temperature was significantly reduced from 25 hours minimum to 10 hours minimum.
- Lycoming Engineering determined this process change to be Minor.
- The stress relief and straightening process can impact residual stresses and associated fatigue strength of the crankshaft.

An unsigned Lycoming internal memorandum dated June 16, 1999 to J. Helminiak, (Lycoming Engineering) from E. Bordy (Lycoming Materials Laboratory) requested a change to the crankshaft straightening process. The memorandum states in part, "Many crankshafts were straightened at 10 hours and these shafts have been successfully straightened when the run-out was rechecked. Because of the large volume of crankshafts that have been successfully treated in this manner, it is therefore requested that LPS-496 be changed from held at heat for 25 hours minimum to held at heat for 10 hours minimum". Lycoming could not provide the SCRT with any further substantiating documentation, which defined how they evaluated and approved the change such as analysis, metallurgical examination, part or engine endurance testing.

v. Summary of Process Changes: The SCRT review of three major Lycoming Process Specification changes (ECO's) relative to crankshaft manufacturing indicate inconsistent levels of substantiation, documentation, and change classification by the company. Of primary concern is the improper identification of process changes that should have been classified as major design changes as these types of changes can impact the durability of the finished part.

LESSONS LEARNED

a. Lack of PAH Supplier oversight for critical processes: The primary contributor to the root cause of the crankshaft failures is lack of adequate supplier control by the PAH. Lack of adequate supplier control can result in process deviations that can have significant effects on the service life of critical reciprocating engine parts.
b. Changes to Critical Processes: The FAA does not have clear policies and guidance addressing substantiation of changes to critical processes, or changes in suppliers who perform critical processes. Confusion exists between what is covered in the type design and what is not.
c. Inadequate Special Process Specification: The PAH forging specification was determined to be insufficient and lacked the necessary detail to adequately control forging temperatures. Inadequate process specificity can lead to variations in supplier process methods and procedures that can have significant effects on the service life of critical reciprocating engine parts.
d. TBO Substantiation: Certification compliance programs for derivative reciprocating engine models of increased power do not typically re-validate the TBO in accordance with FAR 33.19. Performance of the 150 endurance test is insufficient to validate TBO's beyond 600 to 800 hours, so additional testing should be performed, or manufacturer to implement a "lead the fleet" program to determine/increase TBO.

e. FAR 33.43 Bending Stresses: Compliance with FAR 33.43 does not typically address the effect of bending stresses on crankshaft fatigue life. Bending stresses are assumed to be proportional to engine power, and therefore it is assumed that the time at max power during the endurance test is sufficient to validate an acceptable material endurance limit.

f. Classification of Major Design Changes: Classification of major design changes and associated substantiation can vary widely amongst reciprocating engine manufacturers.

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RECOMMENDATIONS

a. FAA Regulations and Policy Relating to Oversight of Critical Processes: FAA regulations and policy relating to oversight of critical processes performed at either a supplier, or at the PAH, should be strengthened to require surveillance on critical part process suppliers. The failures stems from a lack of adequate supplier control by the PAH, failing to ensure the critical process supplier had adequate controls over the maximum forging temperature.

b. FAA Regulations and Policy Relating to Validation of Critical Processes: FAA regulations and policy relating to validation of critical processes performed at either a supplier, or at the PAH, should be strengthened to require formalized Critical Manufacturing Process Validation (CMPV) systems. The CMPV system should be integrated into the initial certification process and design change control system to track to ensure FAA ACO oversight of new and/or changed processes.

c. Durability/TBO Substantiation Guidance: ANE should publish policy and/or guidance describing durability and TBO substantiation compliance methods for new and derivative reciprocating engines.

d. Vibration Testing Guidance: ANE should publish policy and/or guidance addressing substantiation compliance methods for vibration testing under 33.43. In particular, this policy should address bending stresses.

5. INSTALLATIONS/OPERATIONS WORKING GROUP

INVESTIGATION

The Special Certification Review Team (SCRT) Installations/Operations Working Group was tasked with evaluating published data and procedures related to installation and operation of the Lycoming TIO-540 engine. The working group reviewed the documents listed in Appendix 1and conducted the following on-site reviews to accomplish this task:

- Lycoming: October 29,2002, March 6,2003 and June 24/25, 2003.
- Piper: January 28/29, 2003, Feb. 10, 2003, April 23, 2003.
- Cessna: January 10, 2003 and March 4, 2003.

a. Installation Evaluation:

The SCRT evaluated specific procedures utilized by the primary airframe manufacturers, Piper and Cessna, and compared the installation designs incorporated by those airplane companies to the installation procedures provided by Lycoming. A summary of documents reviewed for this task is shown in Appendix 1.

The initial review of installation data was conducted at Lycoming. Data reviewed consisted of Detail Engine Model Specifications provided to the OEM installer, Operators Manuals provided with each engine and service publications provided to the field for various turbocharged 540 series engines. Based upon satisfactory review of this data, a review of the application of this data at the airframe manufacturers facility was accomplished at Piper and Cessna. Piper and Cessna were selected for the evaluation, as they are the most active current users of these engine models. Upon completion of the initial review at the airframe manufacturers, a follow up meeting was conducted at Lycoming to discuss the results of the visits amongst the team members and discuss follow-on activities.

The installation evaluation at Piper included the review of documentation associated with the Piper Model PA-46-350P, Malibu Mirage (see Figure 5-1). This model was selected due to the high incident rate of crankshaft failures. This evaluation included the review of the Powerplant Substantiation Report for the PA-46-350P, the Pilot's Operating Handbook and data from the Service Difficulty Report database sorted for the model PA-46-350P, as well as a physical review of the engine installation in current production PA-46-350P aircraft. Piper engineering was extremely open and supportive in the conduct of this review. The two initial visits to Piper allowed for a thorough review of the documentation related to the engine installation and its recommended operating procedures. The final certification review meeting at Piper included SCRT team members that had previously visited Cessna to accomplish a similar review and combine these efforts in an attempt to be as objective as possible in the overall assessment of the Piper installation of the Lycoming TIO-540-AE2A engine. No powerplant design characteristics were found during these reviews that could adversely impact crankshaft durability. The powerplant installation design was found to be consistent with Lycoming design data and requirements.

The installation evaluation at Cessna included the review of documentation associated with the Cessna Model T206H Turbo Stationair (see Figure 5-2) that is equipped with the Lycoming TIO-540-AJ1A engine. As with the Piper Mirage, this aircraft model was selected due to the high rate current production and reported crankshaft failures. The initial review at Cessna was accomplished by an individual SCRT team member to review the history of the certification process as related to the Cessna Model T206H airplane. . As with the final review at Piper, the final Cessna review included a SCRT member that had conducted the initial review at Piper. During the initial and final certification review at Cessna, adequate documentation was made available to ensure the SCR Team that Cessna addressed all aspects of Lycoming installation guidance and limitations as well as the pertinent FAR requirements. As with the Piper review, no powerplant design characteristics were found that could adversely impact crankshaft durability.

Figure 5-1
Piper Malibu Mirage

Figure 5-2
Cessna Turbo Stationair

b. Operation Evaluation:

The SCRT evaluated the available operational instruction data provided by Lycoming during the initial certification effort to verify that this data was properly and clearly incorporated in the Piper and Cessna instructions during aircraft certification. The SCRT also evaluated the data available from Lycoming in regard to detonation and detonation margin to verify that this data was utilized and verified during aircraft installation certification efforts at Piper and Cessna. In addition, the operational procedures provided by non-OEM (non-TC holder) organizations that provide such information to the public at large were reviewed. These organizations include AOPA, GAMI, and fleet operators.

The Operator’s Manuals provided to the SCRT by Lycoming include recommended operating practices and procedures for the various turbocharged 540 series engines subject to the review. These procedures include general instructions for starting, shutting down, preflight and in-flight limitations and procedures for normal and extreme environments. In-flight information includes recommended power settings for various altitudes and environmental conditions. The manuals contained sufficient information and were organized in a concise manner such that installers and operators could both adhere to the manufacturers recommendations.

The Piper Pilot Operating Handbook for the PA-46-350P, Mirage, included information as highlighted above from the Lycoming Operators Manual for the TIO-540-AE2A engine and expanded where necessary for this particular installation. The Piper handbook was arranged for the pilot to utilize the information provided in a clear and logical format. No discrepancies were noted between the Lycoming and Piper operating recommendations.

The Cessna Pilot’s Operating Handbook for the T206H airplane with the Lycoming TIO-540-AJ1A engine also included information from the applicable Lycoming Operators Manual. However, recommended cruise power settings contained in the Cessna POH specify slightly higher fuel flow settings relative to those recommended by Lycoming. This will always provide for more detonation margin as long as the prohibition against Lean Of Peak (LOP) operation specified in this same manual is adhered to (see below discussion on LOP). Once again, this material was provided in a clear and logical format. No discrepancies affecting crankshaft durability were noted between the Lycoming and Cessna operating recommendations.

In addition to the manufacturers recommendations discussed above, Lycoming provided the operational procedures utilized by a typical fleet operator, AmeriFlight, a California based company. These procedures were evaluated against the recommendations of Lycoming, Piper and Cessna. The fleet operator's procedures typically were more conservative in power settings and leaning margins than that expressed in the applicable manufacturers recommendations.

The SCRT also issued an Airworthiness Concern Process sheet through AOPA surveying both fleet and private operators for their typical power settings for take-off, climb and cruise operations. The purpose of this concern sheet was to perform a final validation of the acceptance of the manufacturer's recommendations by operators.

Information provided through AOPA that discussed operating procedures at several fleet operators indicated that other commercial operators adhere to these conservative settings. Information on these fleets indicates positive impact on engine durability and TBO result from these conservative operating procedures.

c. Lean of Peak Operations:

As a follow-on effort, data available to the flying public regarding lean of peak operation and the margins associated with installed detonation margin were evaluated by the SCRT.

Various non-OEM organizations have offered information to the flying public in regard to operating reciprocating aircraft engines with fuel flow settings lean of peak exhaust gas temperature. These procedures have been offered as a means to achieve fuel consumption figures below those recommended by the engine and airframe manufacturers. The OEM manufacturers procedures for their products reviewed during these SCRT activities, Lycoming TIO-540-AE2A and TIO-540-AJ1A engines, Piper PA-46-350P and Cessna T206H, do not permit lean of peak operation. In the case of the Cessna POH, these operations are specifically prohibited. Lycoming provides its negative position regarding lean of peak operation in its publication SSP700. This publication indicates that while lean of peak operation was recommended in the late 1960's, it no longer recommends the practice due to a multitude of problems encountered. As previously stated, fleet operator data evaluated by the SCRT indicates that these operators consistently encourage their pilots to utilize engine power setpoints that are more conservative (rich) than those recommended by the engine and aircraft manufacturers.

Concluding, it is the determination of the SCRT that lean of peak operations not be approved unless the engine and aircraft manufacturer explicitly approves it. This position is based upon the following (see Figure 5-3):

1. Engine instrumentation. The minimum certification standard of engine instrumentation as shown in 14 CFR 23 is inadequate to monitor engine parameters during lean of peak operation. Both additional individual cylinder instrumentation and properly maintained and accurate instruments are required if lean of peak operation is desired. In many cases, margins for the installed engine have been expanded due to known instrument inaccuracies. The selection of engine instrumentation by the airframe manufacturer is based upon minimum certification standards and the balance between expected aircraft operating methodologies and cost.
2. Reduction in detonation margin. Lean of peak operations may allow the engine to be operated with fuel consumption values below that shown in the engine and aircraft operator's manuals for best economy. Operation at these lean fuel air ratios, even at power settings below seventy-five percent, brings the individual cylinder operating conditions to a point at which minor disturbances in overall engine airflow, such as minor power adjustments, disruptions in the engine induction system or changes in ambient operating conditions (altitude or OAT), may result in leaner than anticipated fuel air ratios for an individual cylinder or the engine and lead to a detonation event. The failure of the pilot to first richen the mixture during power changes, altitude changes or emergency conditions may also yield a detonation event. Spark plug condition and consistency of magneto timing becomes even more critical when lean of peak operations are attempted.
3. Pilot training. As indicated in Item 1 above, additional instrumentation is typically required to perform lean of peak operations. The pilot must be aware of the operation of this instrumentation and its limitations. Monitoring of this expanded instrumentation requires pilot attentiveness beyond that of the normal aircraft engine instruments. Loss of some or all of this instrumentation must force the pilot to revert to a more conservative fuel management approach, irrespective of his experience level in operating lean of peak. As indicated in Item 2 above, the proximity of the engine to detonation also requires additional pilot

attention and adherence to operating procedures that are typically not contained in the engine or aircraft operating manuals. Leaning below the levels specified in the manuals requires slow and precise manipulation of mixture control such that individual peak cylinder exhaust gas temperature values may be determined. When operating at temperatures below peak, minor throttle manipulations to recover power lost during the leaning operation may yield detonation conditions. The failure of the pilot to first richen the mixture during power changes, altitude changes or emergency conditions may also yield a detonation event.

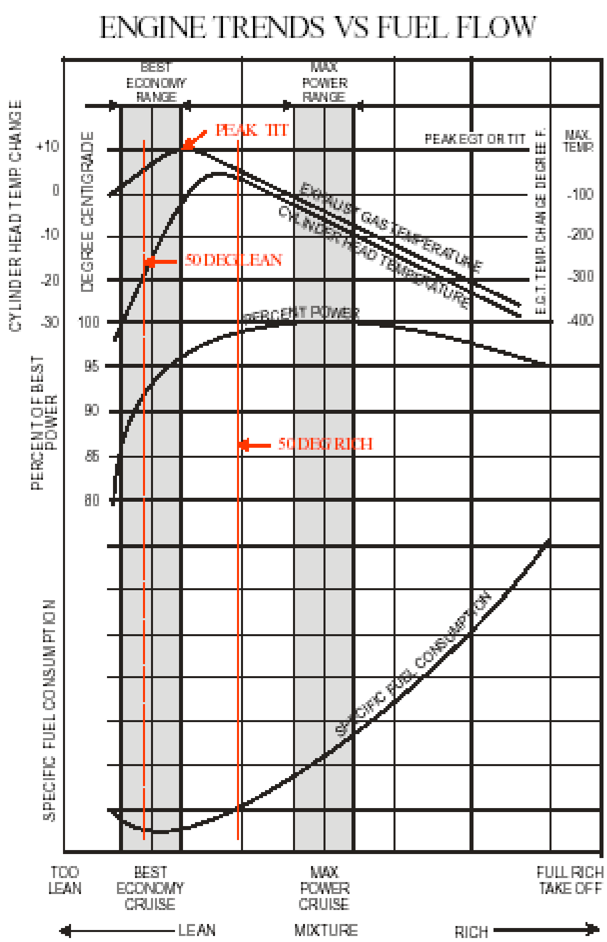


Figure 5-3
Engine Trends vs Fuel Flow

LESSONS LEARNED

a. Fleet Operator Procedures: Fleet operators of reciprocating engine-powered General Aviation airplanes typically use conservative operating procedures relative to detonation margin.
b. Lean of Peak Operation: Lean of Peak operation can lead to inadvertent detonation if the airplane is equipped with inadequate engine instrumentation, the aircraft/instrumentation is not maintained in accordance with manufacturer's requirements, and/or the pilot does not make mixture adjustments when engine power or ambient conditions change.

RECOMMENDATIONS

a. LOP Informational Bulletin: ANE should work with ACE to publish an informational bulletin or article advising of the risks of LOP operation.
b. Engine Management: ANE should work with Flight Standards regarding the development of educational programs for pilots about topics such as fuel mixture management, turbocharger operating procedures and engine maintenance issues in GA aircraft that may be included during recurrent training seminars and the Wings program.

6. Stress Analysis Working Group

INVESTIGATION

The program developed by Lycoming and the Stress Analysis Working Group relied on the collection of experimental test data to develop and refine analytical models. These analytical models were used to estimate the stresses in critical regions of the crankshaft and those stresses were used to determine the fatigue life of crankshafts manufactured from clean material and to assess the service life of crankshafts manufactured from honeycomb material.

a. Definitions

The following provides a translation for some of the terms found in the subsequent discussion that are not self-explanatory.

Fatigue life analysis; a means of predicting the number of applied load cycles that will cause initially sound material to exhibit crack initiation. Potential contributing factors include but are not limited to magnitude of cyclic stress oscillation, oscillation frequency, local geometric stress concentrations, number of accumulated peak stress cycles, material fatigue strength characteristics, min-to-max stress ratio, and operating environment.

Internal stress; this is a load per unit area within a structural part, i.e. lbs./sq. in., that results from application of load.

Stress concentration; an increase in stress in the vicinity of a localized geometric transition (such as a radius, a notch, or a change in cross-sectional area). It is numerically expressed as the ratio of the maximum local stress to the nominal field stress.

s-n curve: fatigue life in terms of number of applied load cycles to cause crack initiation as a function of maximum stress .

Applied load cycle; one cycle is a full min-max-min oscillation of loading (the starting point for defining a cycle can be arbitrary, e.g. from zero, min, max, etc.). For a 4-cycle reciprocating engine, the crankshaft is exposed to one cycle of loading per two revolutions.

Fracture mechanics evaluation; a means of predicting the number of applied load cycles that will cause an existing crack to grow to critical size (causing complete failure of the structural part). Contributing factors are the stress field at the flaw (resulting from the applied loading condition), crack geometry, and crack growth related material characteristics.

Stress intensity; essentially a stress gradient in the immediate vicinity of a crack tip. It is a function of the local stress field, crack length, and a crack geometry factor. Stress intensity along with material crack growth behavior characteristics, determines the crack growth rate.

Fracture toughness; identified as K_{1C}, is the maximum value of stress intensity that a particular material can tolerate. When this value is exceeded, failure occurs by fast fracture.

Crack growth rate; identified as da/dn, it is the incremental increase in crack size after exposure to each cycle of applied load.

Threshold flaw size: the crack length above which a crack will propagate for a given stress level.

Critical flaw size; the crack length above which a crack will fail in an unstable and unpredictable fashion. (critical flaw size is a function of K_{1C}, applied stress, and other factors). Between the threshold and critical flaw sizes, crack growth and cycles to failure can be predicted by application of the appropriate theory.

Initial flaw size; crack length at beginning of crack growth predictions. It would represent a material defect size or separated grain boundary length, or could be an assumed value for a design analysis.

Residual stress; locked in state of stress that is present in a part which is not subjected to any external loads. Residual stresses can be created by mechanical working, thermal processing, or by treatments intended to alter the surface of the material.

Finite Element Model; abbreviated FEM, is a computer simulation of structural behavior based on modeling continuous structure as a mesh of discrete nodes connected by a network of relatively simple structural elements. The nodes define spatial geometry while the elements represents the local stiffness and mass properties of the local region within the mesh. Boundary conditions (attachments) and external loads are applied as nodal constraints on applicable elements. Output of the program includes element loads and stresses, and nodal deflections. In general, prediction accuracy improves with increasing mesh density (number of nodes and elements) so a complex structure may require a very large number of discrete nodes and elements. As a result, raw output data is very cumbersome (large tables of numbers – page after page), so analysis results are usually reprocessed for presentation as a graphical depiction of deflected shapes and stress distributions, or produced as a very limited table of stresses, deflections, or other desired characteristic, for a very small region of the model.

Finite Element Analysis: the application of FEM and denoted as FEA

CMM; Coordinate Measuring Machine, it is a computerized micrometer tool used to generate surface geometry in 3 dimensions.

b. Crankshaft Analysis Overview (see Figure 6-1)

The following represents an overview of the complete stress analysis program. Subsequent sections will address each element of the analysis in more detail.

i. Experimental Test Data

Experimental test data from engine and component testing was required for calibration and correlation of the computer simulations. The following three tests were performed:

1. LMS Component Structural Dynamics Testing: Components from the engine drive-train (crankshaft, crankcase, pistons, connecting rods, and cylinders) were tested to define the l building block mode shapes and natural frequencies for the crankshaft, drive-train sub-assembly, and built-up (not rotating) engine. The component and sub-assembly modal data was used to validate component finite element models.
2. Crankshaft Static Stress Test: A test rig was developed to measure the strain in the crankpin fillet radius and crossover cheek while the cylinder was statically pressurized at fixed crank angles. This data was used to calibrate the crankshaft finite element stress model.
3. Engine Test: The Lycoming instrumented engine test was performed to provide measurements of dynamic strain, lateral and torsional vibration, and combustion pressures at corner point operating conditions for validation of the multi-body simulation model.

ii. Computational Analyses and Key Outputs (see Figure 6-1)

The computational analyses and their key outputs are summarized below:

1. NASTRAN Finite Element Model (FEM): This is a mathematical representation of the mass and stiffness of the crankshaft. The model was used to calculate mode shapes and stresses of the crankshaft.

2. Multi-Body Simulation (MBS): This model couples the flexible crankshaft model (from the FEM) with translating rigid piston and connecting rod masses, rotating propeller inertia, propeller aerodynamic loads, flexible bearing models, cylinder pressure time histories (from the engine test), and system friction losses to model the dynamic engine system under operating conditions. Primary model outputs are crankshaft load and deflection time histories at a limited number of load interface points between the crankshaft and its supporting structure.
3. Stress Recovery: In this analysis the crankshaft deflections from the MBS are applied to a modal model constructed from the FEA calculated mode shapes to back calculate stresses at critical points of interest in the crankshaft.
4. Fatigue Analysis: The maximum stress from the stress recovery is compared to the crankshaft fatigue endurance limit to determine if fatigue damage will occur during engine operation. This will determine the service life of crankshafts manufactured from material without the honeycomb features.
5. Fracture Mechanics: The stress distribution from the stress recovery is used to calculate minimum flaw, or crack sizes necessary for propagation of the flaw to occur under normal engine operating loads. This service life of the crankshaft with honeycomb features is then assessed based on the threshold flaw size, service experience, and size distribution of actual flaws.

Each of the above items is reviewed in more detail in the following sections.

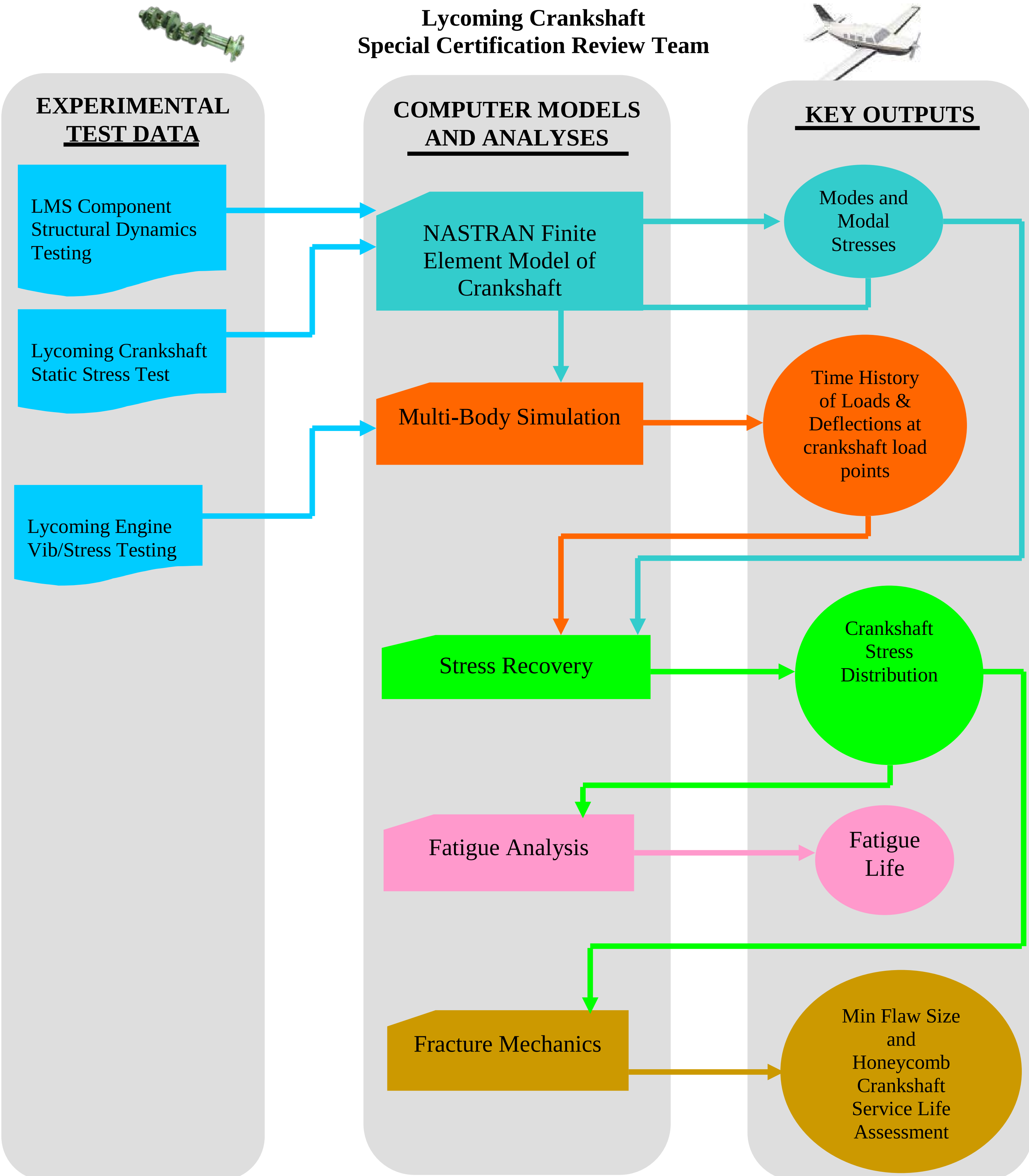


Figure 6-1
Crankshaft Analysis Overview

c. Experimental Test Data

Experimental test data from engine and component testing was required for calibration and correlation of the computer simulations. The following three tests were performed:

1. LMS Component Structural Dynamics Testing: Components from the engine drive-train (crankshaft, crankcase, pistons, connecting rods, and cylinders) were tested to define the dynamic response (vibration mode shapes and frequencies) of the engine and crankshaft. These components were tested both separately and as built-up assemblies by measuring vibration response when excited by an instrumented hammer strike while being suspended at each end from bungees (in what is described as "free - free" support). Results of this investigation were used to calibrate the flexible mode shapes in the FEM. Photos of the test set-up along with pictorial representation of the lateral bending response are shown in Figure 6-2.

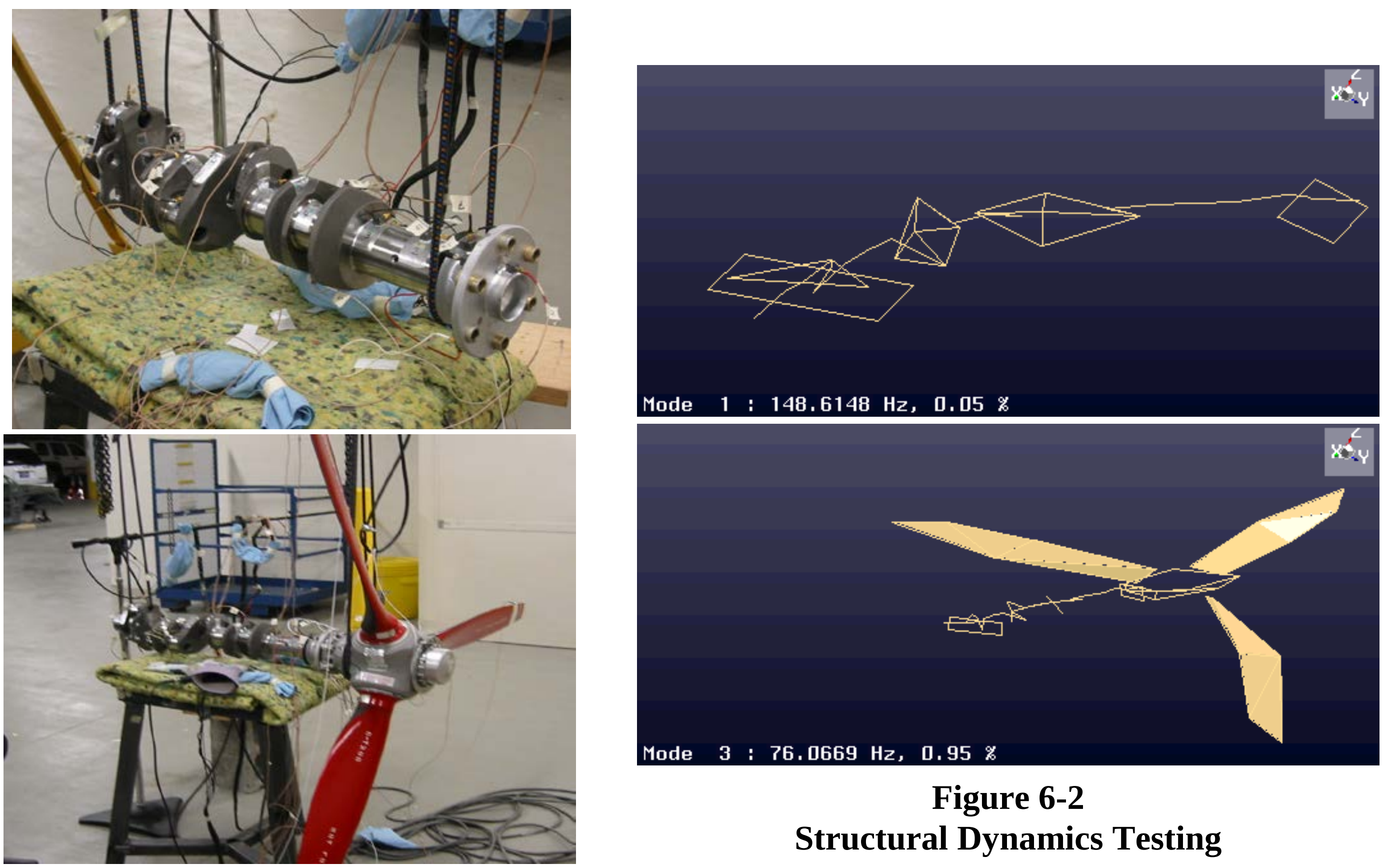
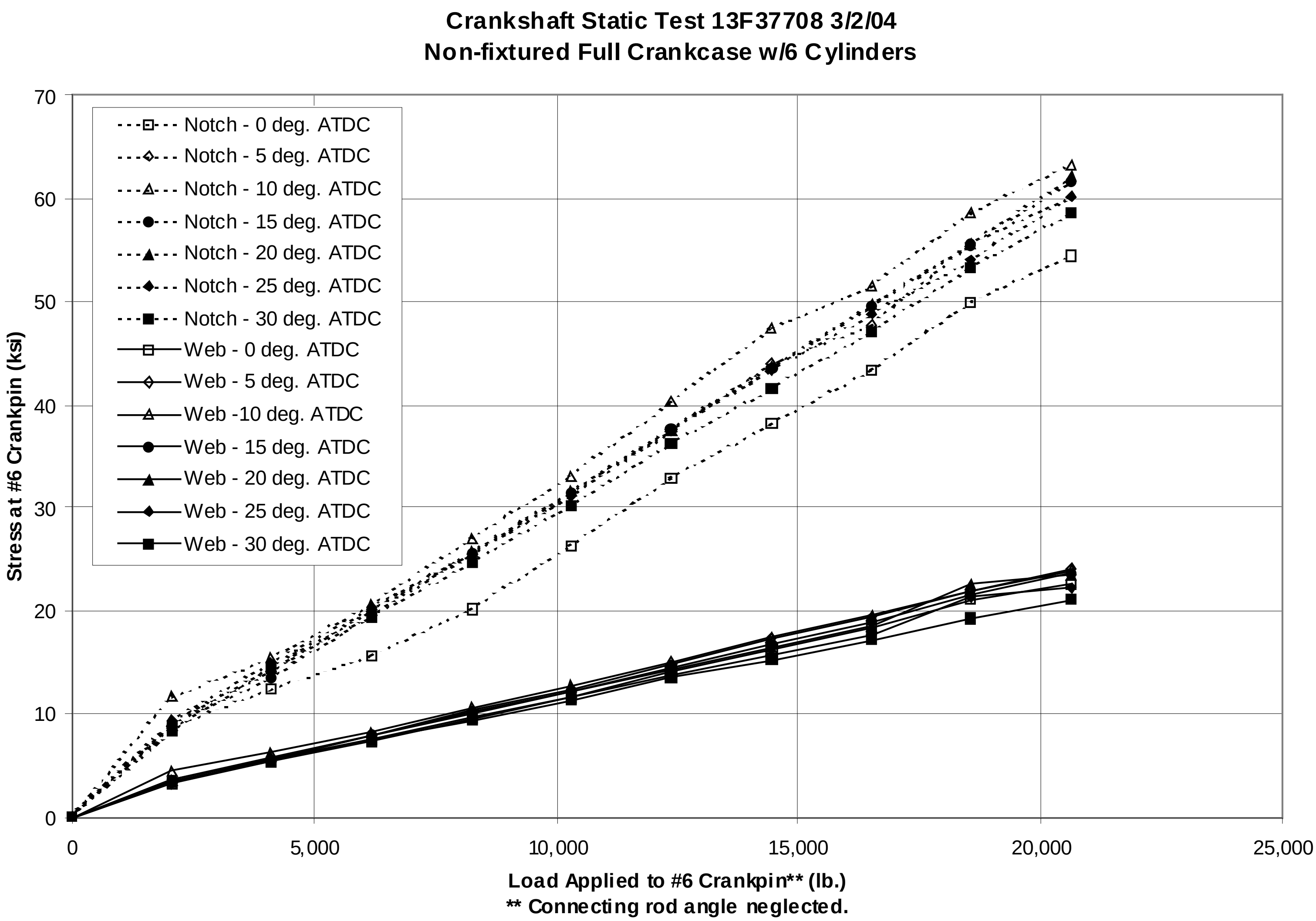


Figure 6-2
Structural Dynamics Testing

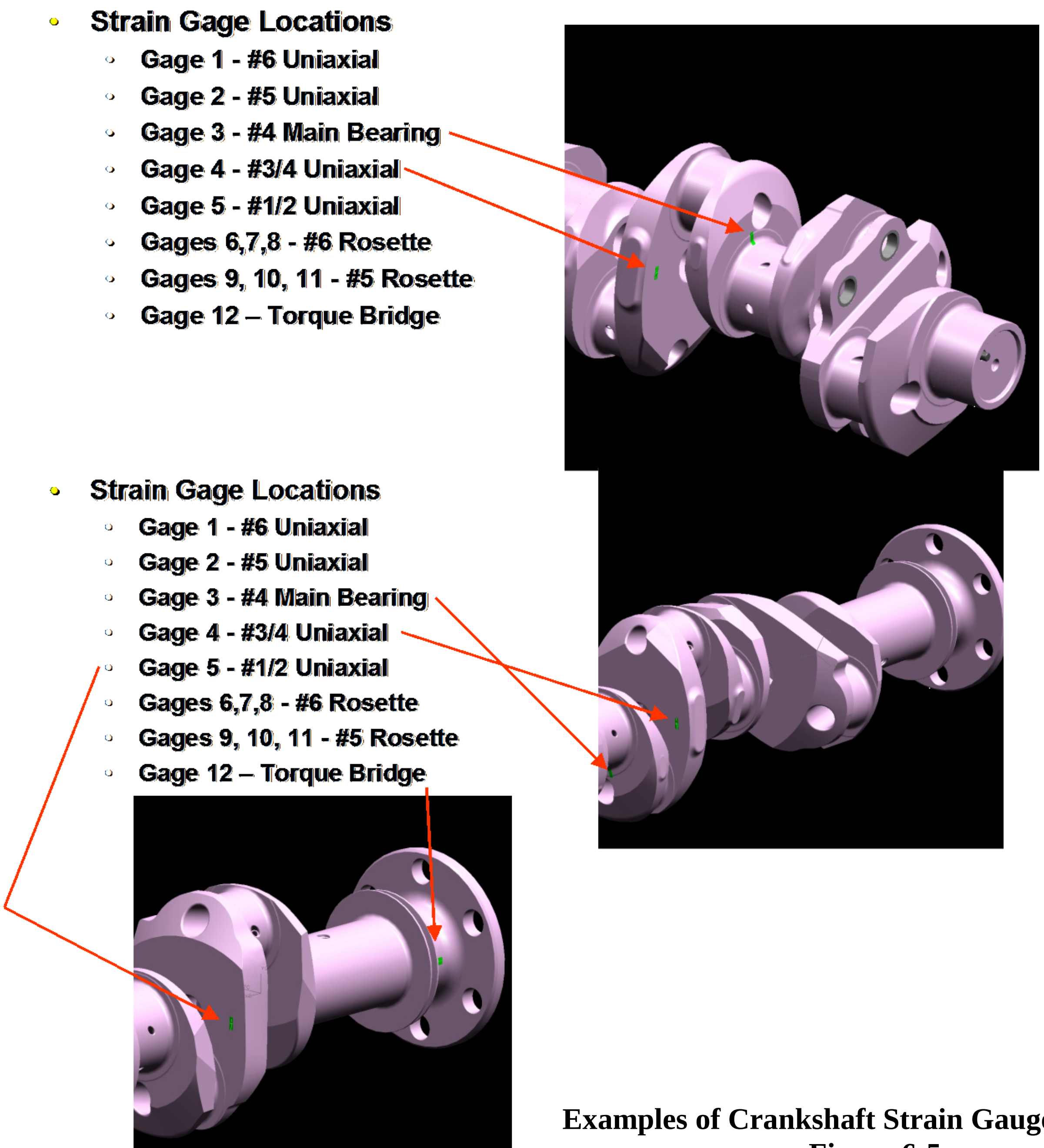
2. Crankshaft Static Stress Test: The lack of clearance between the connecting rod bearing and crankshaft journal precluded the installation of a strain gage in the no. 6 crankpin fillet radius during the operating engine stress survey. The strain could only be measured at a location on the crossover cheek in close proximity to the fillet radius. Therefore, it was necessary to experimentally determine a correlation factor (called the notch factor) between the measured stress at the cheek and the stress at the fillet radius. To accomplish this, a test rig was developed to statically measure the strain in the crankpin fillet radius and the crossover cheek under the same applied load. The notch factor under tensile loading conditions was found to be approximately 2.6. The results from this test were used to calibrate the stress calculation in the FEM. The test rig is shown in Figure 6-3 and test results are shown in Figure 6-4.

Crankshaft Static Stress Test Rig
Figure 6-3



Crankshaft Static Stress Test Results
Figure 6-4

3. Engine Test: The purpose of the engine test was to measure actual stresses on the crankshaft along with engine and crankshaft vibratory response during operation. The stresses were measured at specific locations on the crankshaft at specific operating conditions and these data points were used for calibration of the MBS. The vibratory data was used to validate the dynamic characteristics of the engine models. Figure 6-5 illustrates the measurement locations that were used to characterize crankshaft response during the operating test. Strain gauges were installed at the locations indicated by the red arrows in the images.



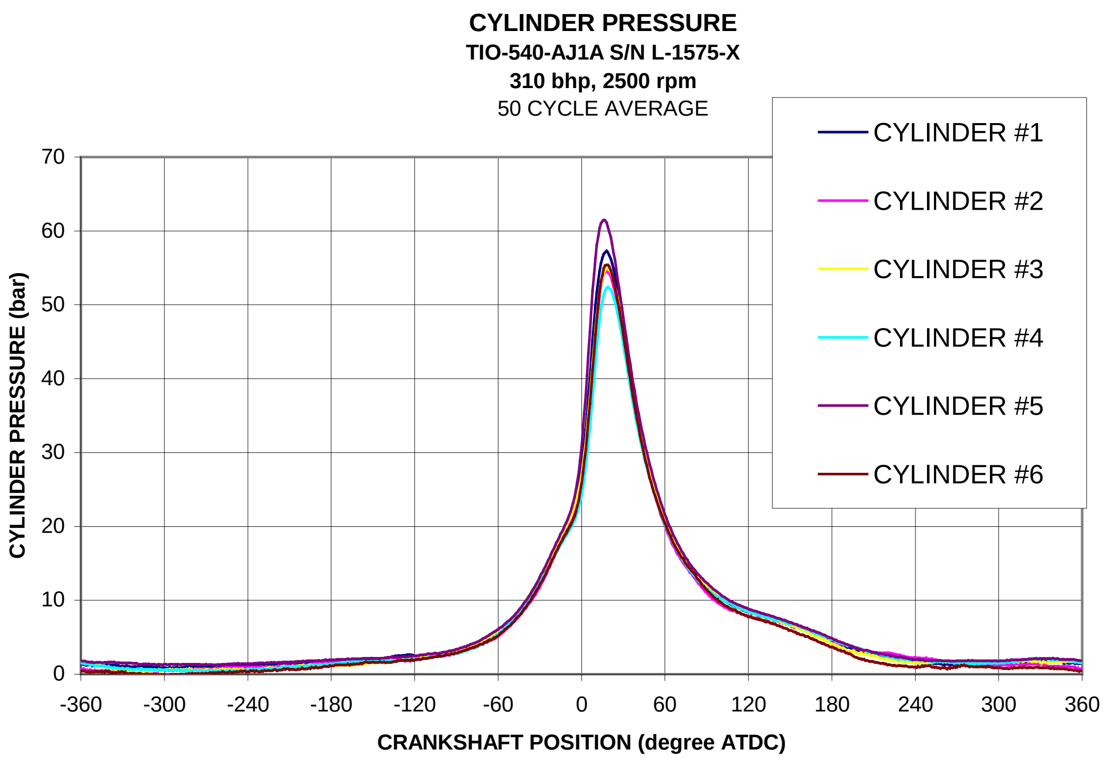
Examples of Crankshaft Strain Gauge Locations
Figure 6-5

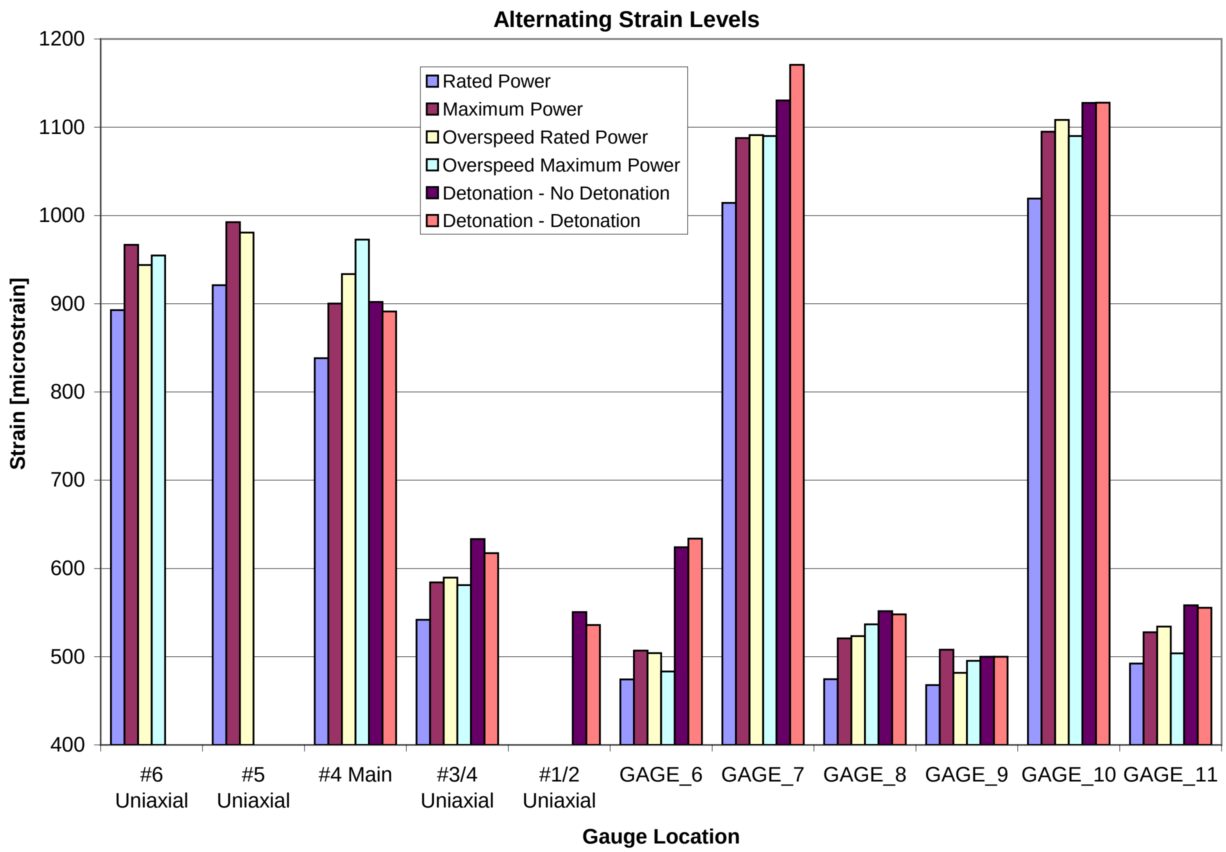
A TIO-540-AJ1A engine model was selected for the test. This engine model has experienced a disproportionate number of failures relative to its lower power rating (310HP) and several of those occurred at low time since installed new. The crankshaft installed in this engine is a “wide pin, large pin diameter” configuration crankshaft (see Figure 2-5). The engine was tested in the “flight stand” test chamber at Lycoming’s Williamsport, PA facility with an instrumented crankshaft to obtain operating crankshaft stress data. Testing began in late June 2003, and was successfully completed in late July 2003. After expending significant effort to verify proper instrumentation operation, all test plan conditions were accomplished in about 3 days.

The test operating load conditions were as follows;

- Idle: Min. throttle @ 800rpm
- Rated load / speed: 310HP @ 2500rpm
- Max. load / speed: 350HP @ 2500rpm
- Cruise: 233HP @ 2400rpm
- Overspeed: 310 & 350HP @ 2750rpm
- Detonation: 310HP @ 2500rpm - detonation induced by leaning to best economy fuel flow, increasing oil temperature (temp.), and throttling of the turbo inlet.
- rpm sweep: Idle to 2500rpm @ fixed low pitch, near- linear rpm increase in approximately 2 sec.

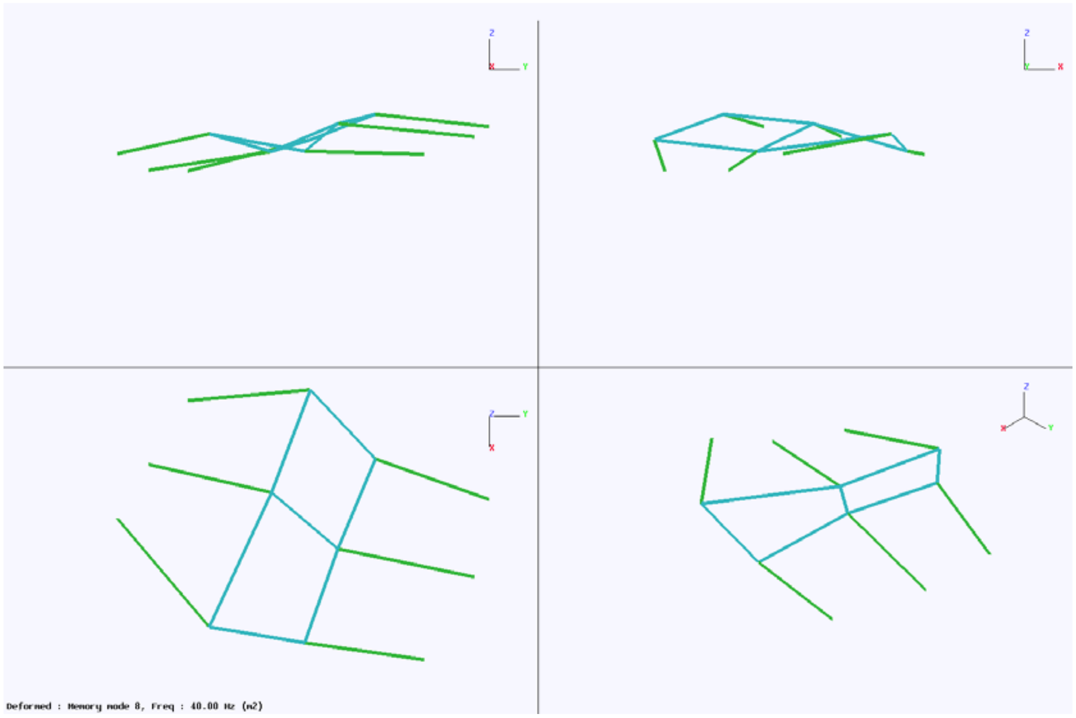
An SCRT member witnessed much of the actual testing, during which some of the critical operating conditions were run, and partial data recorded. The test engine was configured with only those accessories needed to operate the engine for the test (i.e. starter, magnetos, fuel injection system, propeller, exhaust manifold and turbocharger). Accessories that only support aircraft systems such as alternators and vacuum pumps were not installed and their absence was determined to not have any influence on the test results. The test cell provides engine mount support, fuel (at pressure), induction and cooling air, engine oil (filtered, at pressure, and temp. controlled), exhaust gas venting, and engine controls (throttle, propeller rpm, and fuel mixture). Engine and test cell instrumentation was in place to record crankshaft speed (rpm), fuel flow, turbo outlet pressure (pres.), manifold pres., induction air pres. and temp., ambient test cell pres. and temp., cooling air temp., oil temp., turbo inlet temp., crankshaft rotational position, crankshaft strains, and crankcase vibration accelerations. All data was captured synchronously with time and crank position so that data reduction for any transducer could be performed against time or crank position. During the test, data was recorded to computer hard drive then later transferred to CDs for archiving. . A sample of some of the test data is shown in Figure 6-6 (alternating strain and cylinder pressures), Figure 6-7 (engine shape deflection), and Figure 6-8 (crankshaft torsional vibration).



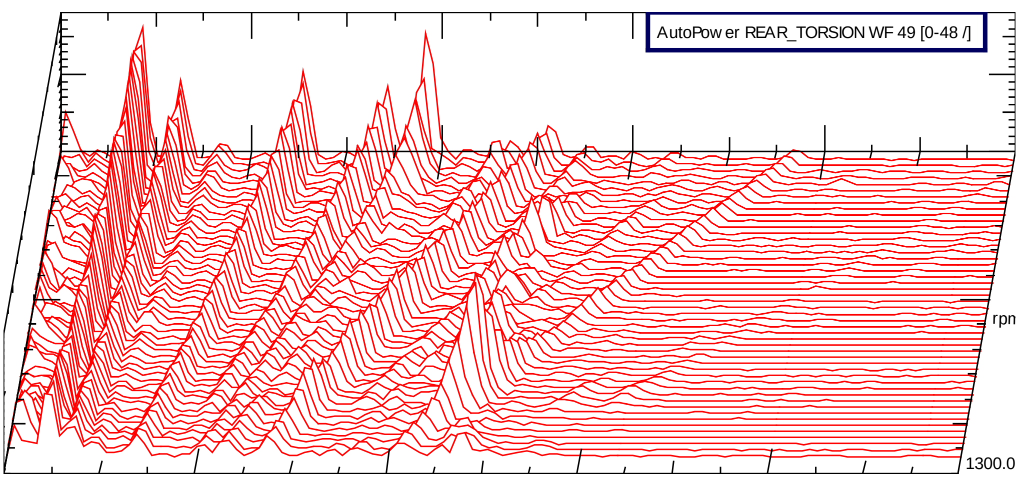


Example of Engine Test Stress Survey Data

Figure 6-6



Engine Operating Deflection
Figure 6-7



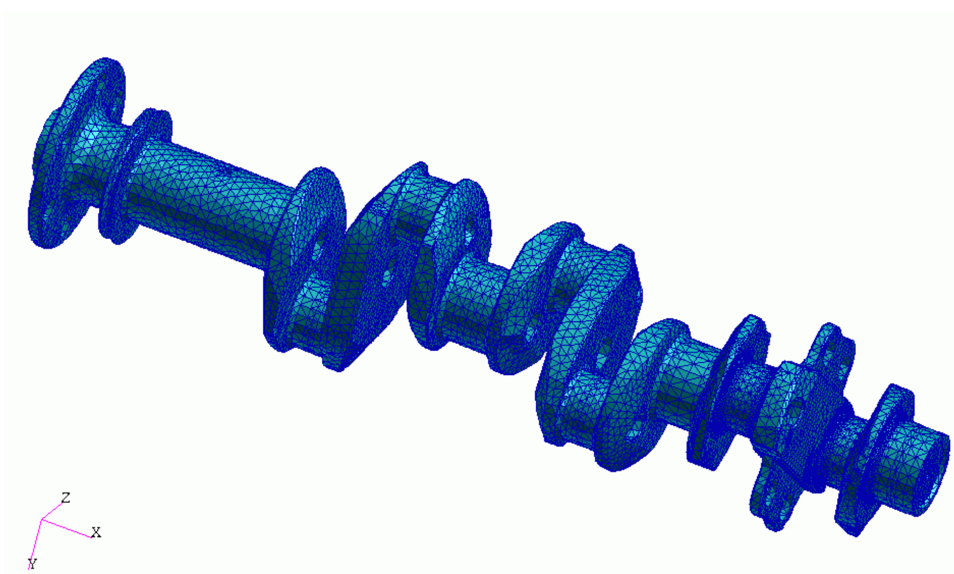
Crankshaft Torsional Vibration
Figure 6-8

d. Finite Element Model (see Figure 6-10)

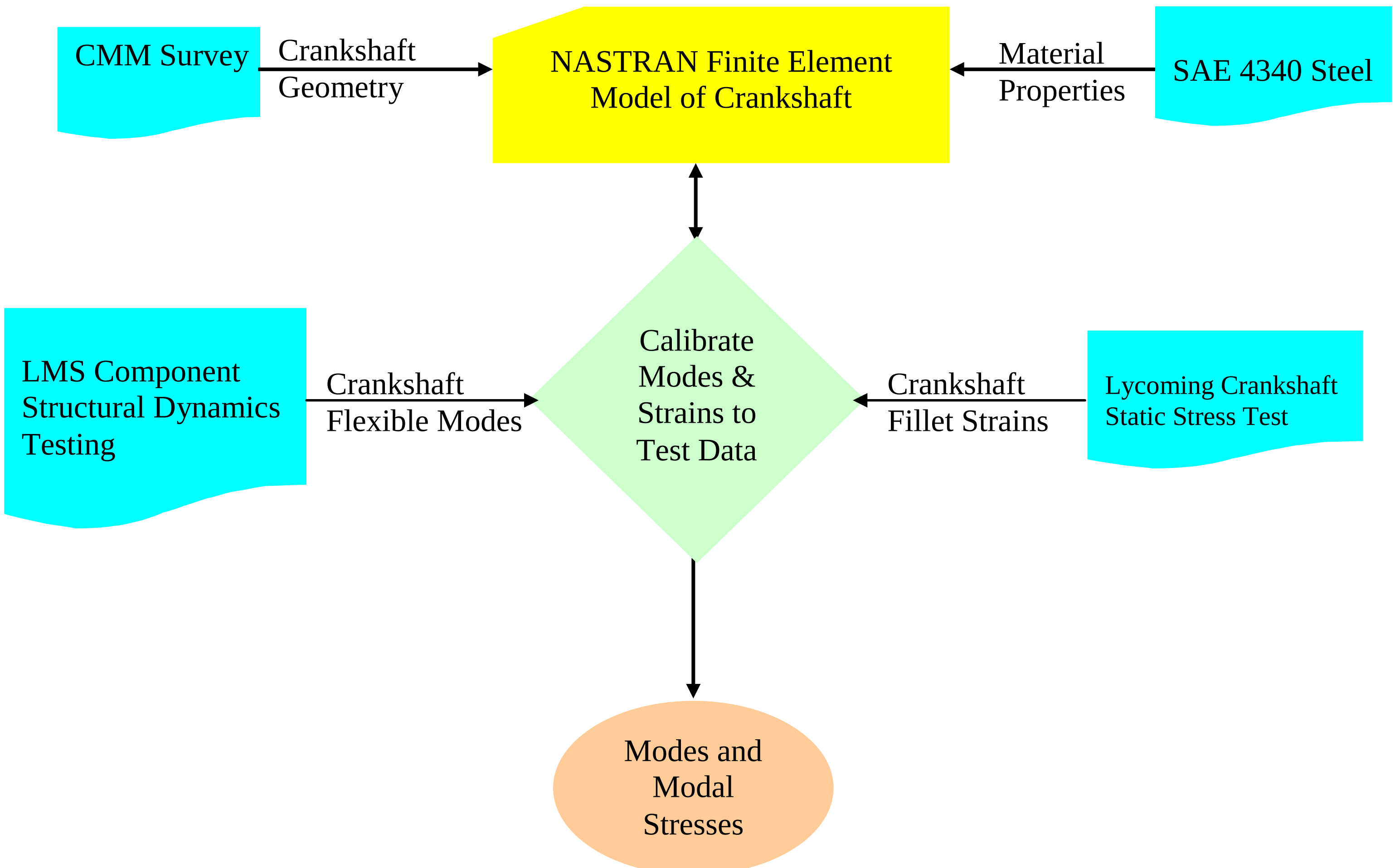
i. NASTRAN FEM

The NASTRAN FEM is a mathematical representation of the mass and stiffness of the crankshaft. Static analysis to determine stress in response to unit loads and dynamic analysis to calculate mode shapes and natural frequencies were performed to generate inputs for the multi-body dynamic simulation and subsequent stress recovery. Lycoming's consultant contractor, LMS - North America, performed the FEM computer analysis. The initial complete definition of geometry, stiffness and vibration characteristics of the crankshaft, load application locations, and load distributions was completed in June 2003. Model validation for static stress prediction was done against the Lycoming static engine test. Dynamic validation of the model was done against the crankshaft component modal test results.

The crankshaft FEM was constructed using 3-D geometry from a CMM measurement of the actual crankshaft used in the engine test. Two FEM's were constructed based on the level of refinement of the tetrahedral elements. The Tet-4 linear fit model had 41,000 nodes (measurement locations) and the Tet-10 parabolic fit model had 296,000 nodes. The Tet-10 model requires significantly more computer processing time so scaling factors were developed to allow Tet-4 results to be corrected to approximate Tet-10 results. A graphical representation of the tetrahedral mesh used to define the crankshaft is shown in Figure 6-9.



FEM Mesh (Tetrahedral Elements)
Figure 6-9



Finite Element Model
Figure 6-10

ii. CMM Survey of Crankshaft

The actual geometry of the crankshaft used in the engine was mapped on the CMM. This data was used to create the external solid geometry definition for the crankshaft structural model. The solid geometry model was then meshed using an automated pre-processing program to define the three-dimensional mesh for the crankshaft FEM. The actual part being tested differed slightly from the manufacturing drawing nominal dimensions due to tolerances or undefined surfaces (typically, un-machined surfaces of a forging) so using the CMM data allows those variations to be captured thus ensuring that the FEM will match the actual test part and eliminate any questions about whether manufacturing variations had any significant effect on model/test correlation.

iii. FEM Output: Modes and Modal Stresses:

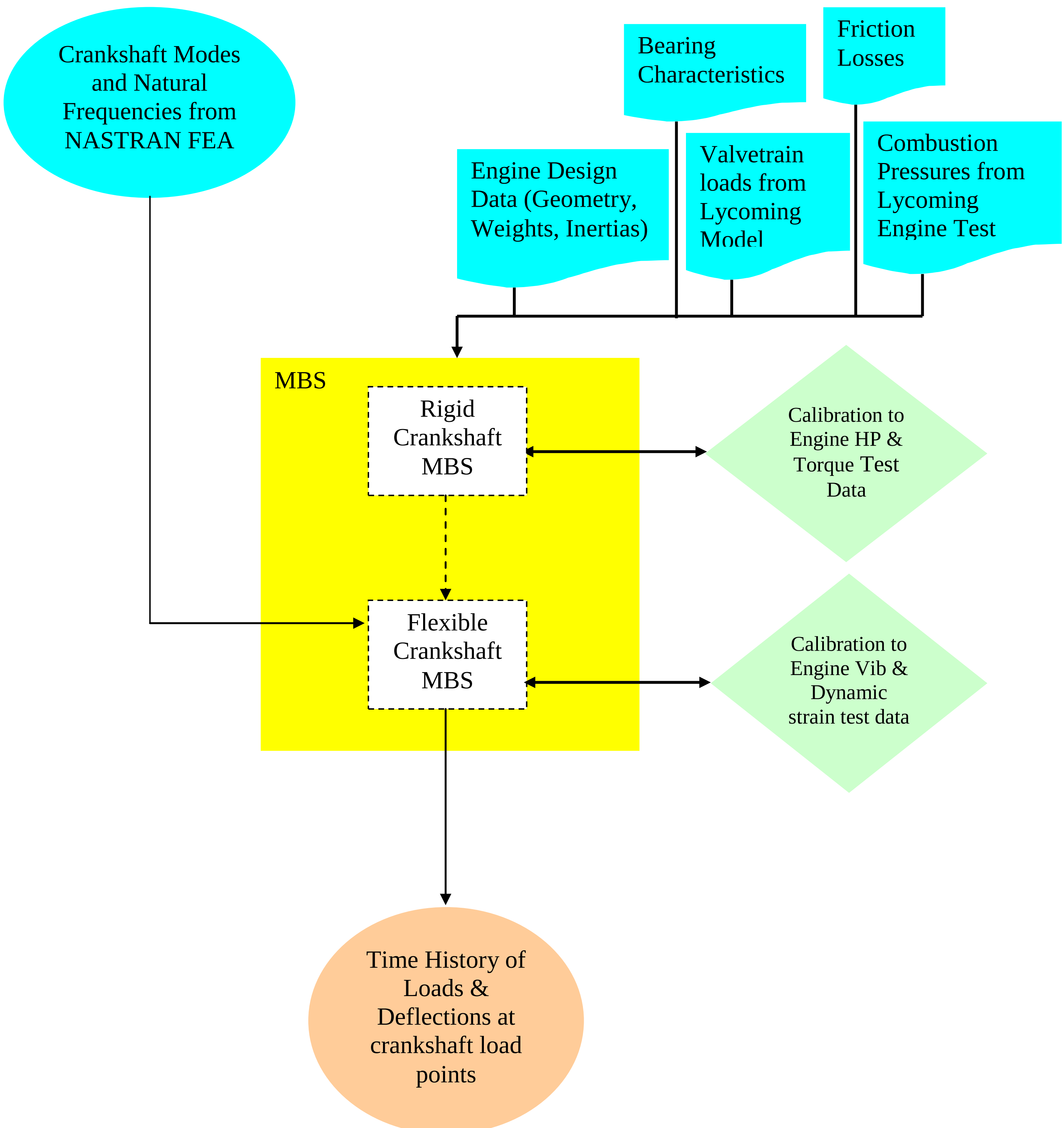
The FEM provides mode shapes and stresses for the crankshaft. The modes and mode shapes are mathematical descriptions of the structural flexibility and are used by the MBS to create transfer functions that model the dynamic response of the crankshaft in the engine. The mode shapes and modal stresses are then used in the stress recovery computation to determine the final stress distribution in the crankshaft.

e. Multi-Body Simulation (see Figure 6-11)

The multi-body simulation (MBS) coupled the crankshaft modal model to the engine drivetrain and supports to simulate the dynamic flexibility of the crankshaft in response to engine operating loads. The MBS was also performed by LMS - North America. The model incorporated 29 rigid body mass elements that represented key engine components such as connecting rods, pistons, and the crankcase, plus the flexible crankshaft model. Kinematic joints were established between each of these elements and applied forces and torques related to combustion, the propeller, gears, and piston friction used to drive the model. A summary of the input data, output data, and calibration of the model is provided below.

i. MBS Input Data

1. Modes and Modal Stresses from the NASTRAN FEM: The FEM provided mode shapes and stresses of the crankshaft inputs to MBS where they were used to create transfer functions that represented the dynamic flexibility of the crankshaft in the engine.
2. Engine Design Data: This was obtained from Lycoming. Data included drawings, and actual measurements, and performance information.
3. Valvetrain Loads: Lycoming developed an experimental MBS of the engine valvetrain to provide gear-end loads.
4. Combustion Pressures: Data from the Lycoming engine test was used.
5. Friction Losses: The constant Coulomb friction force was back-calculated from the total frictional loss calculation used by Lycoming.
6. Bearing Characteristics: Bearing support (engine casing) characteristics were derived from shaker testing conducted during the structural dynamics modal survey. Radial and bending stiffness of the main bearing fluid films was calculated using an LMS subroutine within MBS. An iterative process was used to calibrate the model by varying the fluid film bearing properties until the combined effects of the fluid film main bearings and crankcase flexibility were simulated. Bearing characteristics such as journal loads and lube oil viscosity were used to calculate bearing deflections.



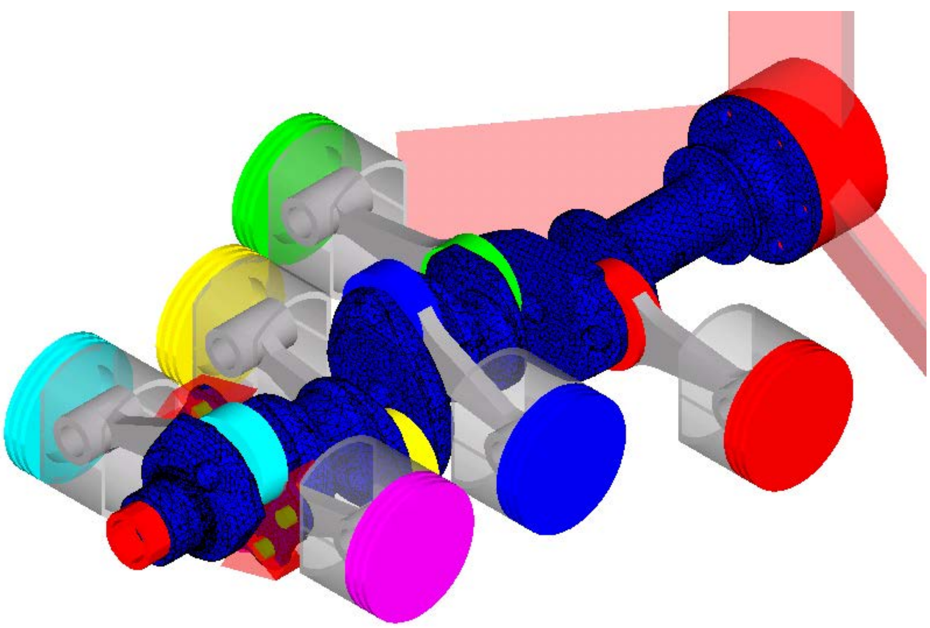
Multi-Body Simulation
Figure 6-11

ii. Rigid Crankshaft MBS:

Initially, a rigid (or non-flexible) crankshaft was run in the MBS to validate that the cylinder pressure profile, friction losses, and prop loading produced the HP and torque loads for the operating conditions of interest. Engine performance data from the engine test was used for this validation. An iterative process was used to refine the model until the horsepower and torque output from the model were within 3% of the corresponding values recorded during the engine test.

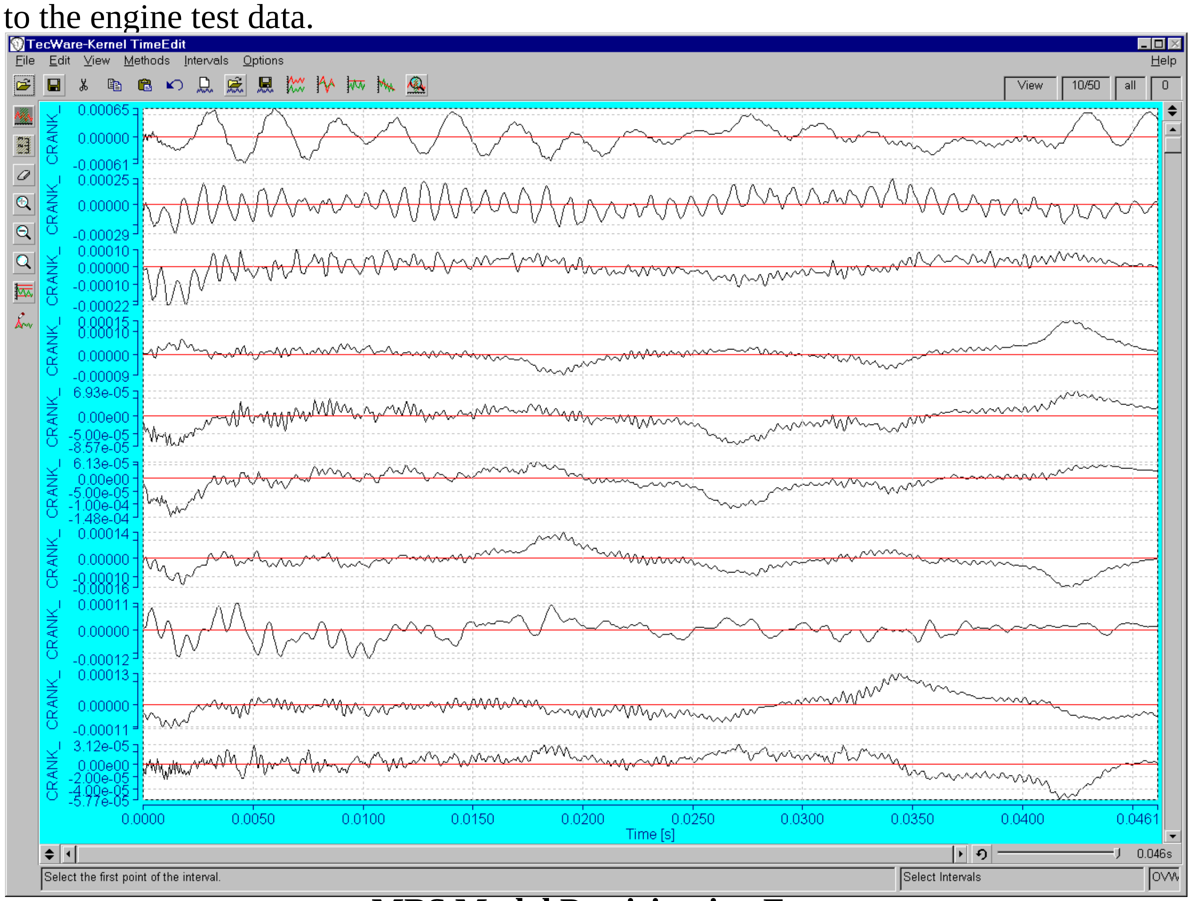
iii. Flexible Crankshaft MBS:

The rigid crankshaft element was then replaced with the "flexible" crankshaft model to calculate the deflections of the crankshaft under operating loads. To reduce computation time, a less refined version of the crankshaft FEM was used for the MBS analysis. Before making this simplification, a sensitivity study was conducted to evaluate critical location scale factors between the coarse and fine models and ensure that stress peaks could be determined accurately with the less refined model. Several engine load conditions were run including a 350HP/2500 RPM max power condition. Vibration and dynamic strain data from the engine test was used to calibrate this portion of the model. A graphic depiction of the drive-train elements of the model is shown in Figure 6-12.



MBS Drive-Train Elements
Figure 6-12

iv. MBS Output: Time History of Loads & Deflections at Crankshaft Load Points: The MBS output consists of load and deflection time histories at specific locations on the crankshaft. Data for a limited number of component connection points (bearings, rods, etc.) rather than for each node in the FEM mesh is calculated to keep the model size at a manageable level. Since MBS is a modal based simulation tool, the output deflections are represented as Modal Participation Factors (MPF's) (see Figure 6-13). The MPF's are scaling factors that are applied to the crankshaft mode shapes for recovery of loads and deflections from MBS and again during the stress recovery step when calculating stresses at the critical points of interest. Review of the initial model results found poor correlation between the model and test. The FAA CSTA advised LMS and Lycoming that the flexibility of the engine crankcase might have been misrepresented in the model because the case/bearing support correlation used by LMS was from a test on an engine case that was artificially stiffened by the test fixture supports. LMS had been relying on automotive analysis experience but aircraft piston engine crankcases are much more flexible than automotive engine blocks and LMS had not recognized the importance of the support differences. LMS then adjusted (reduced) the bearing stiffness in the model to compensate for casing flexibility in the normal operating engine installed configuration and achieved good correlation to the engine test data.



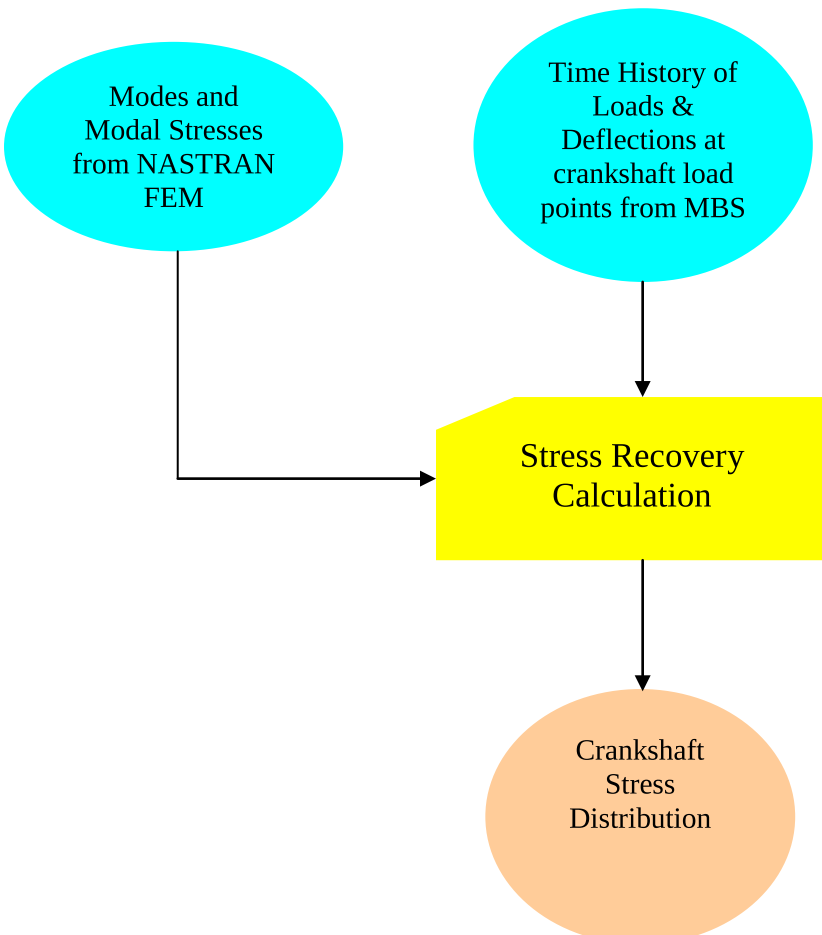
MBS Modal Participation Factors

Figure 6-13

f. Stress Recovery (see Figure 6-14)

1. Stress Recovery Calculation

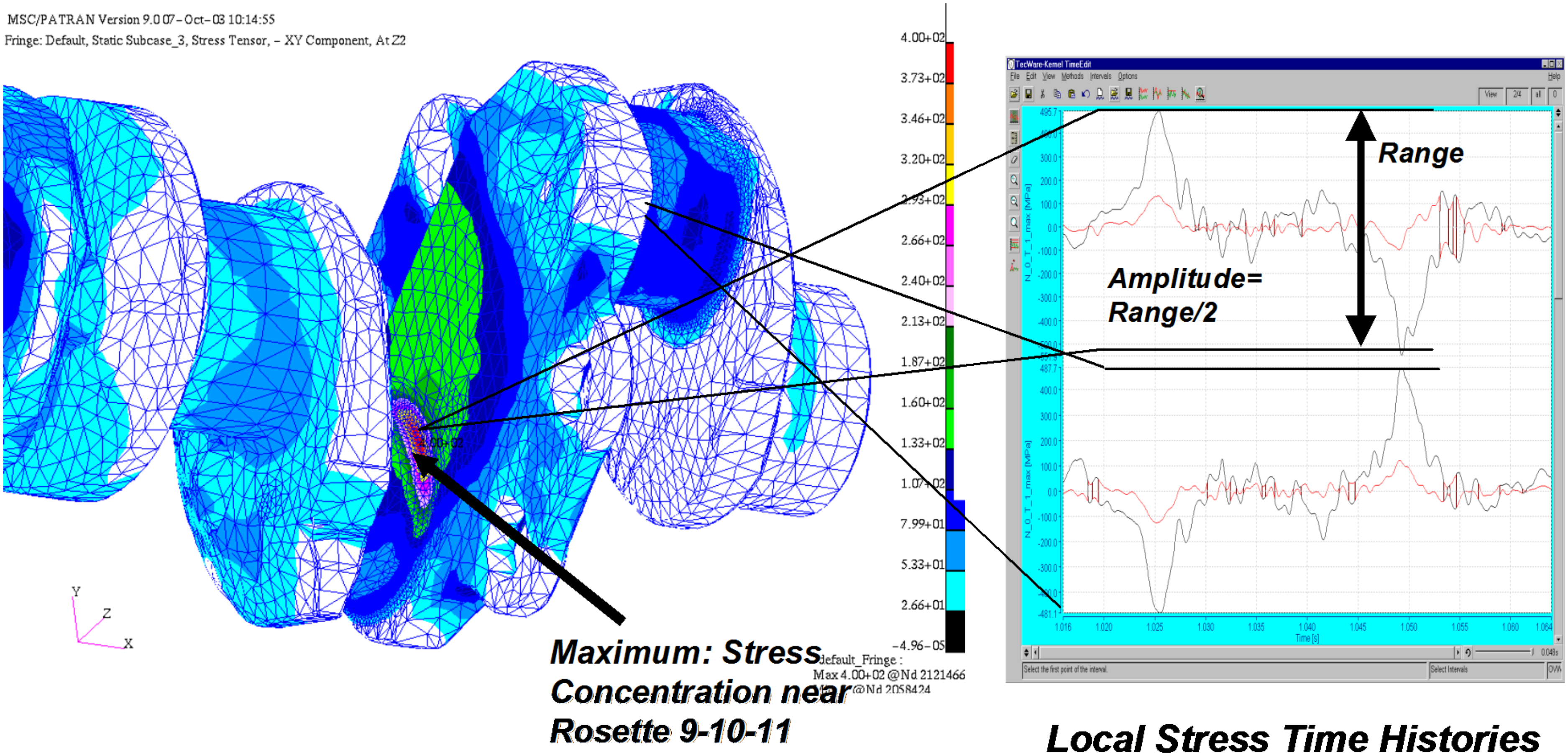
The stress recovery process uses the NASTRAN modal stress vectors to calculate stress transfer functions, then applies the loads and deflections output from the MBS to calculate crankshaft stresses at each engine operating time step. A flow chart of this process is shown in figure 6-14.



Stress Recovery
Figure 6-14

ii. Stress Recovery Output: Crankshaft Stress Distribution

The critical location was found to be at the number five crankpin fillet radius (see Figure 6-15). The maximum surface stress of 89.2KSI occurred at the max power condition (350HP, 2500 RPM). The stress calculated does not include residual stress effects. In addition, the maximum surface stress in the number six crankpin fillet radius (on opposite side of crossover cheek, see Figure 3-3 in Chapter 3) was found to be 79.9KSI.



Location of Maximum Stress
Figure 6-15

g. Fatigue Analysis

The crankshaft fatigue life was evaluated for the 350 HP TIO-540 operating at 2500 RPM, by comparing the max stress amplitude to the material S-N curve to determine the fatigue life. Stresses below the endurance limit (asymptotic portion of the S_N curve) will allow the crankshaft to have an essentially infinite life. See Figure 6-16. Operating stresses calculated for the IO-540 were evaluated in the same manner to evaluate IO-540 fatigue life.

Based on MBS results showing that the no. 5 crankpin journal fillet radius is the limiting location for TIO-540 crank shafts, fatigue life was evaluated at this location both at the surface and at the depth below the surface (.034 in.) where the combination of residual stress and applied-load stress is greatest. The peak subsurface stress location occurs just below the case hardened nitride layer.

The endurance limit was obtained from published fatigue test data for airmelt steel automotive crankshafts, and from measurements made on samples from production crankshafts where Vickers hardness and residual stress could be correlated with material fatigue strength handbook relationships for similar 4340 material. Lycoming did not develop specific material S-N curve for the VAR steel used to manufacture the crankshafts.

Fatigue Life Analysis

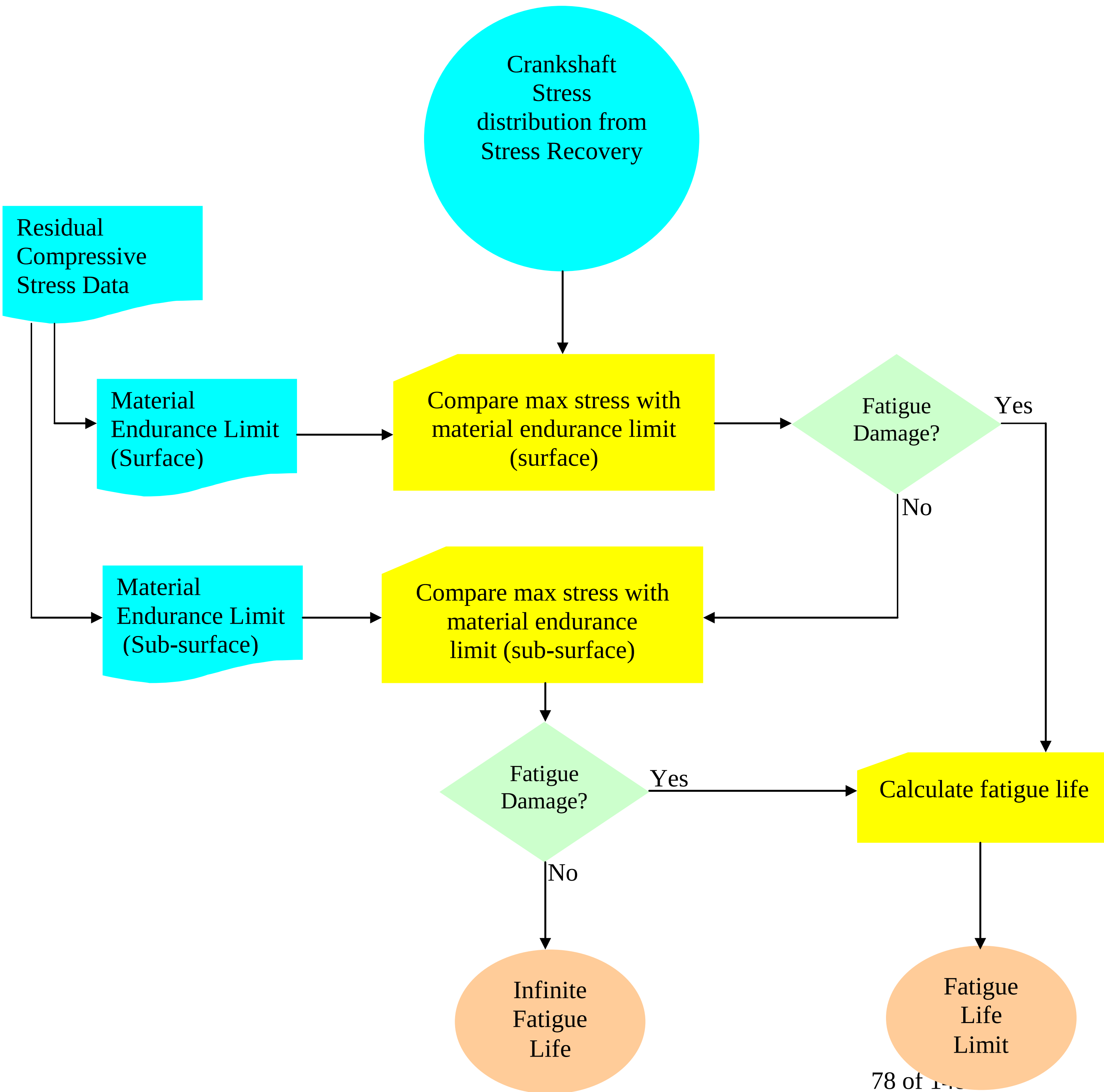


Figure 6-16
Fatigue Life Analysis

i. Residual Stress Investigation

The crankshaft used for the engine test was examined using an x-ray diffraction technique to measure the residual stress due to nitriding with depth below the surface of the crankshaft in the vicinity of the crankpin bearing journal. Residual stress changes the stress-strain distribution with depth and has a significant influence on fatigue life. The residual stress was found to vary from 120KSI in compression at the surface to 10KSI at the critical depth of 0.034 inches. . The measured residual stress distribution was used to evaluate the material endurance limit for the fatigue life analysis, and later in the Fracture Mechanics Analysis to establish subsurface local stresses.

ii. Material Endurance Limit (Surface)

Lycoming/LMS derived a crude estimate for the surface material endurance limit using Vickers Hardness and the residual stress measurements and comparing to published correlations. Four crankshaft specimens were used to measure the Vickers Hardness and the residual stress at the surface. The material endurance limit at the surface was estimated by LMS to be 155 KSI for nitrided material. If the effect of the compressive residual stress from nitriding is disregarded, the surface endurance limit estimated by LMS was reduced to 124 KSI. With the open questions about material processing variations, the SCRT questioned the accuracy of calculating the material endurance limit rather than empirically determining it from fatigue testing of specimens from production crankshafts. The SCRT specimen testing provided limited data from which to estimate a material endurance limit of 125 KSI (FAA fatigue testing of Wyman Gordon crankshaft specimens). The SCRT concluded that the surface material endurance limit of 125KSI should be used for this analysis.

iii. Comparison of Max Stress with Material Endurance Limit (Surface)

Based on test and analysis, maximum stress at the crankshaft surface was found to be +/- 89.2 KSI, which is sufficiently low when compared to the material fatigue strength of +/- 118 to 125 KSI to conclude infinite fatigue life. Based on the range of endurance limits noted in the previous section, this equates to a fatigue safety factor of 1.40 for defect-free crankshafts.

iv. Material Endurance Limit (Sub-Surface)

Subsurface material fatigue strength just below the case hardened nitride layer at the fillet radius was estimated by LMS to be equal to the material yield strength (118KSI). This was based on the results of fatigue testing of airmelt steel automotive crankshafts published in the Boegehold paper . The SCRT believes LMS improperly applied the information in the Boegehold paper in this case, but the 125KSI endurance limit from the

SCRT testing of the Wyman-Gordan specimens is close enough to this value to continue to use 125KSI for the subsurface endurance limit. This however, is a crude estimate, and if a more refined analysis is necessary, actual material S-N data derived from experimental specimen testing would be required.

v. Comparison of Max Stress with Material Endurance Limit (Sub-Surface)

ESI superimposed empirical residual stress data on the LMS stress predictions for the #5 crank pin to calculate the sub-surface stress gradient from the combined effects of the applied stress and residual compressive stress. The experimentally measured residual stress data lacked resolution through the cross section of the crankshaft so ESI applied the measured surface and limited sub-surface residual data to a FEM of the critical crank pin region to predict the subsurface stress distribution. ESI then used a bi-linear curve fit of the FEM results for representation of the residual stress through the area of interest.

The resulting peak combined stress at the critical subsurface location was found to be+ 75.1 to -55.1KSI (see Figure 6-18) at .034 inches below the surface. (Or +/- 65.1 KSI alternating stress with a +10 KSI mean stress offset.) This is also sufficiently low when compared to the minimum estimate of the subsurface material endurance limit of (+/- 125 KSI) for infinite fatigue life. This equates to a fatigue safety factor of 1.66 for defect-free crankshafts.

vi. Fatigue Life Summary

The above results indicate a sufficient margin between operating stresses and material endurance limit to result in an effectively infinite service life for the TIO-540 at the max power operating condition. Fatigue damage at lower power settings should therefore not occur, so it was not necessary to evaluate those conditions. In addition, crankshafts in the IO-540, which operates at lower power and therefore lower operating stress, would also have an infinite fatigue life. Service experience of these crankshafts which indicates that fatigue failures do not occur in shafts with defect-free material.supports this conclusion. In addition, SCRT specimen fatigue testing revealed that at 125KSI max stress none of the samples from the defect-free Wyman-Gordon shafts failed. It should be noted that this infinite life assessment applies only to crankshafts without material defects. The impact of subsurface defects on the crankshaft service life is addressed later in the fracture mechanics analysis.

vii. Effect of Detonation on Fatigue Life

Engine testing revealed a less than expected increase in crankshaft stress during detonation. Lycoming reported an approximate 8%-12% increase in stress for short periods of time during the as-tested detonation condition. This increase does not consume the available margin with the endurance limit and therefore infinite fatigue life can still be assumed for defect-free crankshafts. In addition, service experience indicates that cylinder and piston damage from the high temperatures generated during a detonation event would occur prior to the accumulation of a significant number of cycles on the crankshaft.

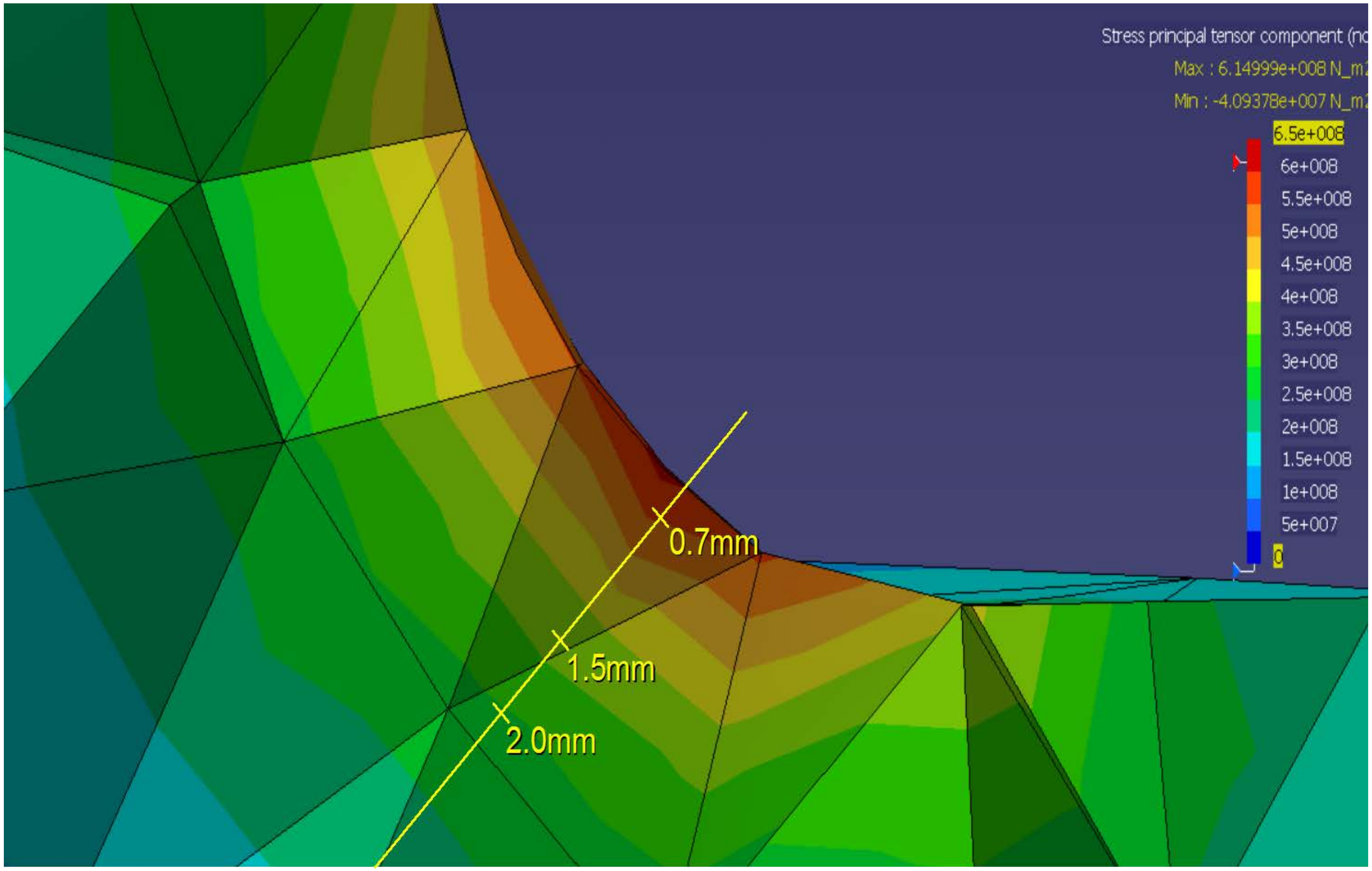


Figure 6-17
Applied Stress vs Depth at Worst-Case Location

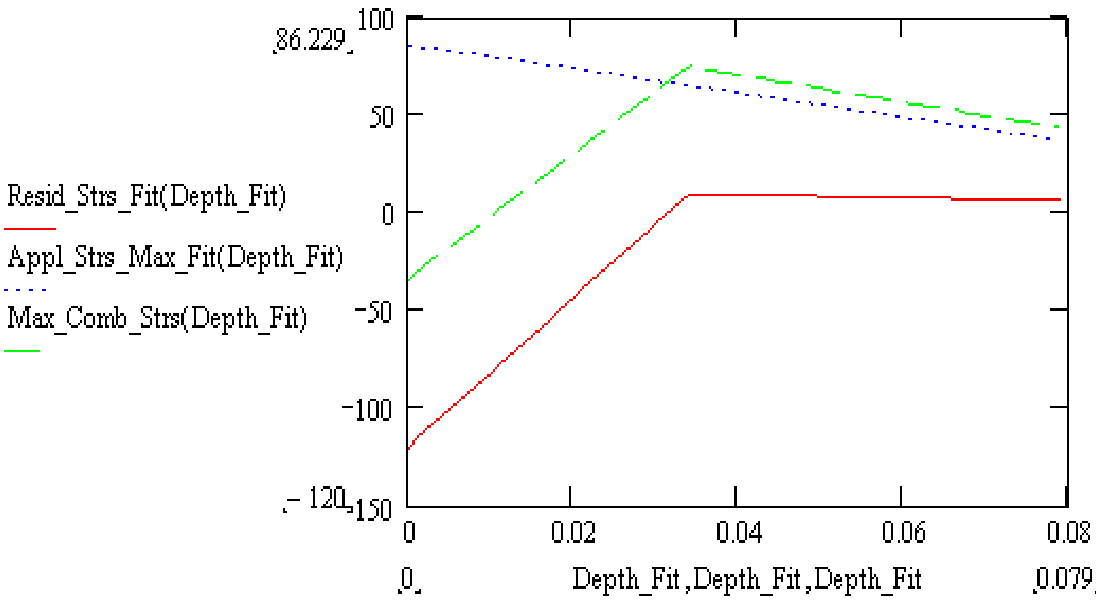


Figure 6-18
Combined Operating and Residual Stresses

h. Fracture Mechanics Analysis

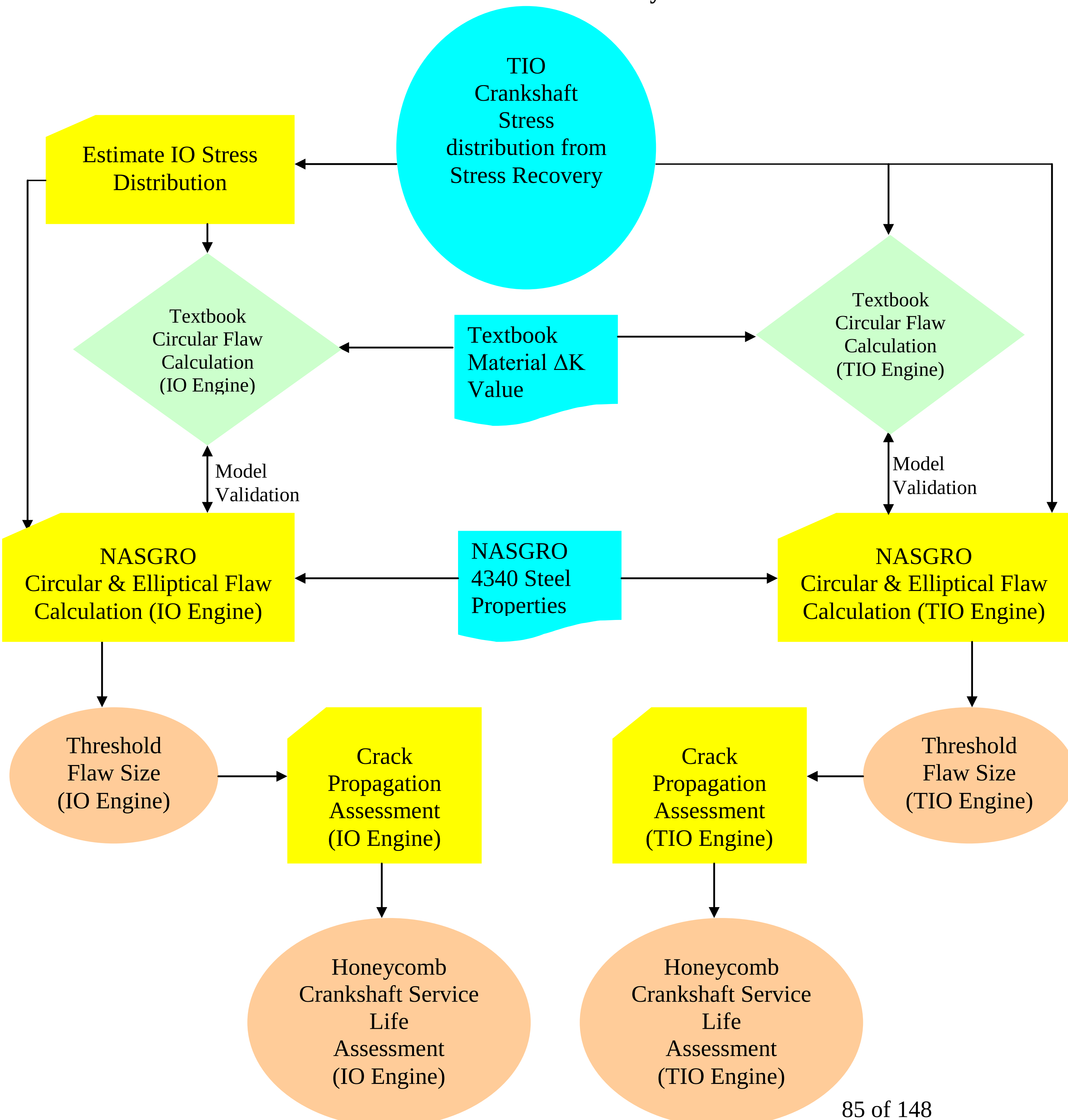
The fracture mechanics based crack growth analysis was performed by Engineering Systems Incorporated (ESI) using Version 3.0 of the NASA fracture analysis program, NASGRO. This analysis predicts the propagation of an assumed embedded elliptical flaw in a body with finite width and depth. The objective of the analysis was to calculate the minimum flaw size necessary for crack propagation, and then to assess the growth of that crack over the service life of both IO-540 and TIO-540 crankshafts. See Figure 6-19.

The ESI analysis determined the initial flaw size necessary for crack propagation at normal operating loads experienced by the crankshaft. The analysis evaluated initial propagation of these cracks at the max power condition. Both the turbocharged (TIO) engines and the normally aspirated (IO) engines were evaluated in this analysis. The following is a summary of key elements of the analysis:

- The analysis was an iterative process that used both the NASGRO crack growth program, and textbook formulas for calculation of threshold flaw sizes based on initial crack growth of embedded elliptical and circular flaws. The textbook solutions were used to validate the NASGRO inputs and initial solutions to make sure NASGRO was tuned to the material and defect size before proceeding with the more advanced elliptical crack calculations. Once the NASGRO calculations were validated against classical "textbook" solutions, the NASGRO elliptical short crack calculations were used for the "real" analysis. Back calculations using the fine-tuned ΔK values from the NASTRAN analysis were plugged back into the textbook classical solution. This confirmed that the classical solution would have given the NASGRO results if the correct inputs were known at the start of the analysis.

- Operating stresses were obtained from the LMS analysis that was previously used for the fatigue analysis. The IO operating stresses were estimated from the the TIO stress data from the stress recovery, with 15% power loss due to installation air induction systems (typical for most airplane installations - from Lycoming data).
- ESI used a bi-linear curve approximation of the nitride residual stresses based on Lambda Research experimental measurement. The residual stresses were then combined with calculated operating stresses to determine the peak maximum combined stresses. The peak subsurface stresses for the TIO and IO engines were determined to be + 75.1 (to - 55.1) KSI and + 57.6 (to - 46.3) KSI respectively.
  - The initial flaw was assumed to be an elliptical shape (aspect ratio of 2), located at the worst-case depth of .034 inches, and with worst-case orientation normal to the direction of principle stress.
  - The NASGRO model provided two results for each engine model; the time for the initial elliptical flaw to grow into a circular flaw, and the growth of that circular flaw during the next hour of operation. The flaw threshold size represents the smallest elliptical flaw (half major axis) that was predicted to continue growing after reaching a circular shape.

Figure 6-19
Fracture Mechanics Analysis



i. Estimate IO Engine Stress Distribution

The stress distribution in the crankshaft installed on the normally-aspirated IO-540 engine model was estimated from the known TIO-540 values. A 15% reduction to these estimated values was applied to reflect installation and ambient losses for the normally-aspirated induction systems.

ii. Textbook Circular Flaw Calculations

The classic long crack theory formula for an embedded circular flaw in an infinite plate was used to validate the NASGRO model:

$$\Delta K_1 = 2(\Delta\sigma)\sqrt{a/\pi}$$

A ΔK_{th} value of 5.5 KSI√in. was selected from textbook data and the positive portion of the stress cycle (75.1 KSI for the TIO) was used for $\Delta\sigma$[1]. The resulting textbook long crack calculation for the radius of the minimum flaw that would propagate at 75.1 KSI was found to be 0.0042 inches.

iii. NASGRO Circular and Elliptical Flaw Calculation

The NASGRO formulation for an elliptical flaw embedded in a finite width plate was used for this analysis (see Figure 6-20).

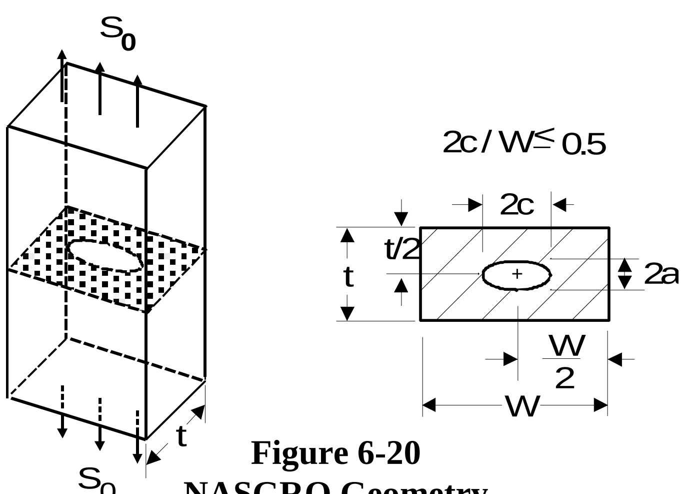


Figure 6-20
NASGRO Geometry

[1] Fracture and Fatigue Control in Structures, Second Edition, John M. Barsom and Stanley T. Rolfe.

A circular flaw was initially run in the NASGRO model using short crack assumptions to compare with the textbook long crack solution. This check was performed to assess the difference between the textbook long crack linear elastic fracture mechanics analysis and the short crack analysis that is available in NASGRO. The short crack analysis accounts for the fact that short cracks tend to grow in conditions where a long crack at the same stress intensity factor, ΔK, would not. NASGRO does this by adjusting the threshold ΔK as a function of crack length and applied stress.

The threshold stress intensity factor (ΔK_{th}) for the long crack solution was determined from handbook data to be 5.5 KSI $\sqrt{in}$ and the corresponding threshold flaw size calculated at 0.0042 inches. When the applied stress and crack radius ("a") were input into the NASGRO model, the threshold stress intensity (ΔK) was calculated by NASGRO to be 4.28 KSI $\sqrt{in}$ and the threshold flaw size calculated at 0.00255 inches. Plugging the NASGRO short crack ΔK back into the long crack textbook calculation reduces the textbook calculation for the min crack size necessary for propagation to 0.00254 inches. Therefore, if the short crack effects were neglected, the required crack size would be overestimated by about a factor of two. However, when the correct stress intensity factor is used, the textbook and NASGRO solutions are virtually identical. The conclusion from this model validation process is that the short crack theory is the correct approach for modeling this problem.
The next step was to determine the maximum allowable flaw size for an embedded elliptical flaw. An elliptical aspect ratio of two was assumed and a sensitivity study conducted to define the threshold flaw size for crack propagation. Since this required an iterative approach, the threshold value was approached from the both the maximum flaw at which propagation would not occur, and the minimum flaw size at which propagation would occur. For the TIO engine, the maximum crack size (radius) at which propagation would not occur was found to be 0.0012 inches, and for the IO engine it was found to be 0.0026 inches.

iv. Threshold Flaw Size

For the turbocharged (TIO) engine, the threshold elliptical flaw size was calculated to be .0013 x .0026 inches (by convention, these are one-half the minor/major axis dimensions) assuming an elliptical flaw with 2:1 aspect ratio. It took 1 hour at max power to grow this flaw to a circular shape with a diameter of .0054 inches. With an additional hour at max power, this crack grew to a diameter of .0134. Based on this analysis, the threshold flaw size is calculated to be .0054 inches. This represents either a circular flaw of diameter 0.0054" or a 2:1 aspect ratio ellipse with major axis dimension of 0.0054".

For the normally aspirated (IO) engine, the threshold flaw size was calculated to be .0026 x .0052 inches (half major/minor axis dimension). After 1½ hours at max power the threshold flaw was predicted to grow to a circular shape with a diameter of .0104 inches. With an additional hour at max power, this crack continues to grow to a diameter of .0138". Based on the NASGRO analysis, the threshold flaw size is calculated to be .0104 inches. As shown by the analysis, the lower operating loads of the IO engines require a flaw that is about twice the size of the TIO threshold flaw for a crack to propagate.

v. Crack Propagation Assessment

1. Defect Size Distribution: A distribution of honeycomb related microcrack sizes was derived by SEM examination of specimens taken from crankshafts. Analysis of this data revealed that the probability distribution of microcrack size shown in Figure 6-22. The minimum flaw sizes from the fracture mechanics analyses and the 95% flaw size are annotated on this curve. The 95% flaw size is a commonly used threshold for crack propagation studies. Figure 6-22 confirms that the 95% flaw size of 0.014 inches is in fact greater than the flaw sizes necessary for crack propagation in both the IO (0.0104 inches) and TIO (0.0054 inches) engine models.

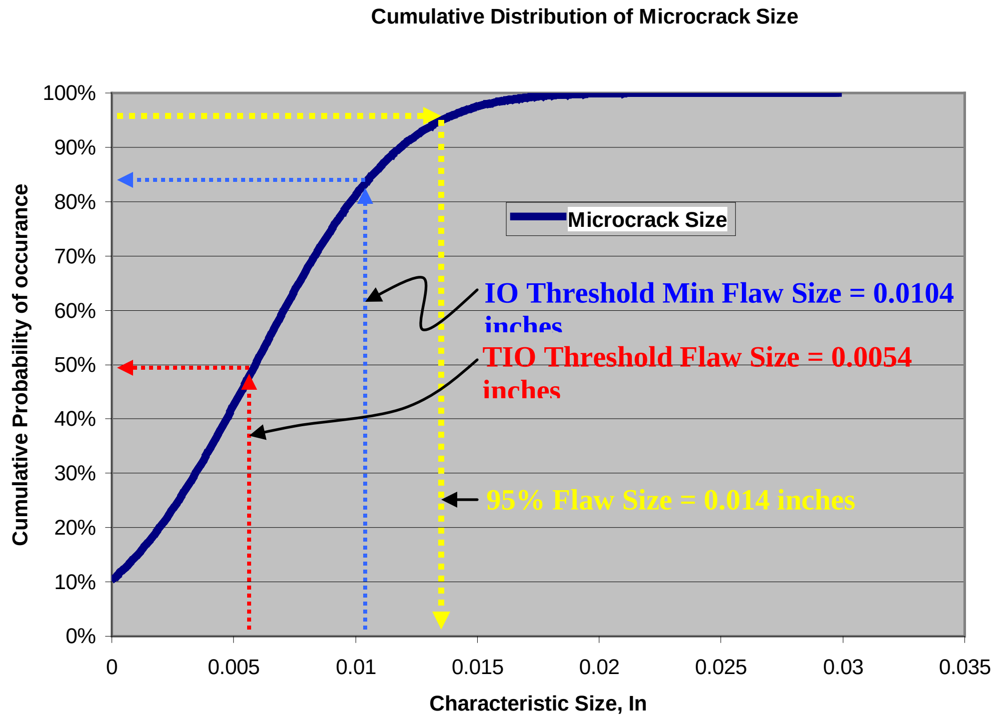
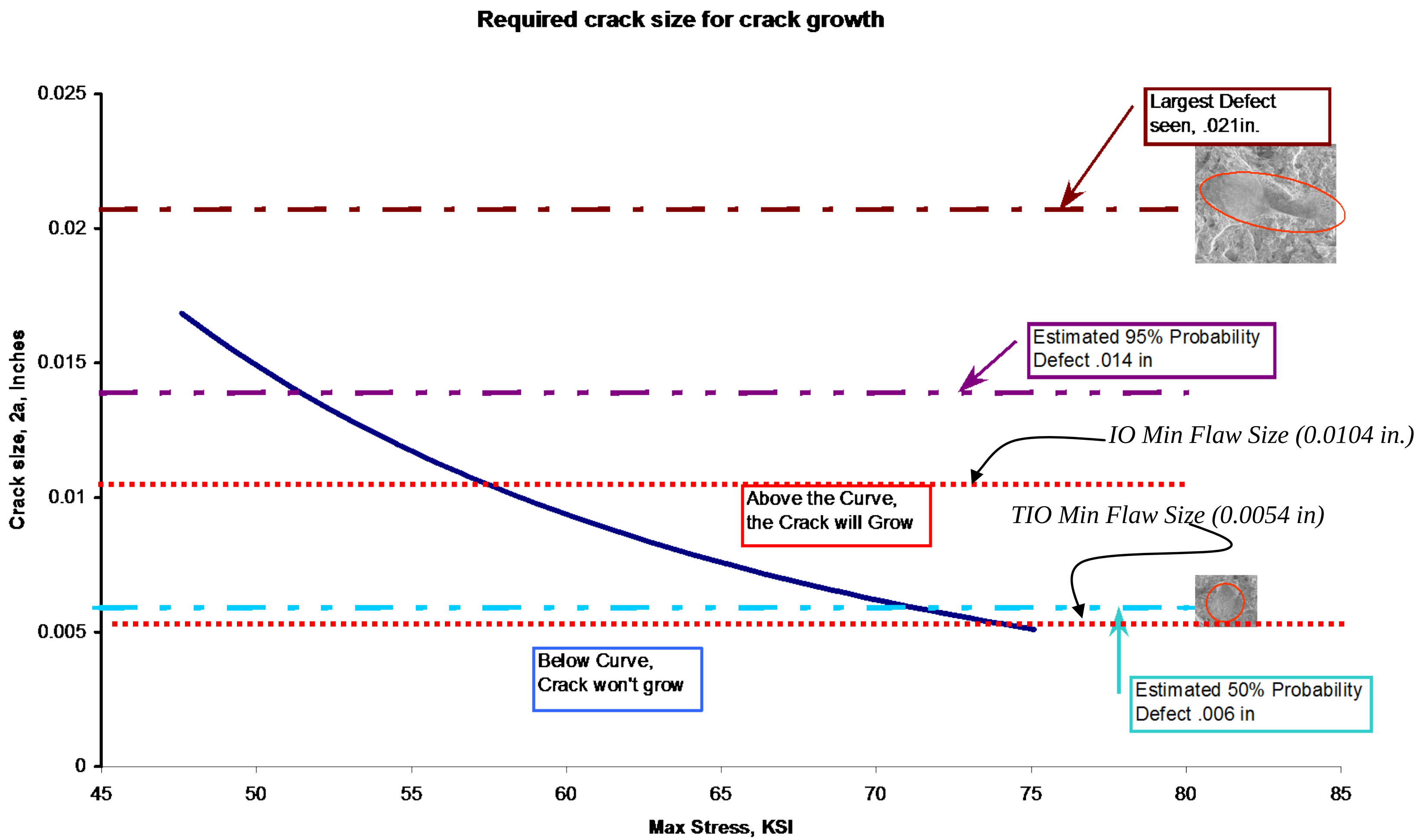

Cumulative Distribution of Microcrack Size
Cumulative Probability of occurance
Characteristic Size, In
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
Microcrack Size
IO Threshold Min Flaw Size = 0.0104 inches
TIO Threshold Flaw Size = 0.0054 inches
95% Flaw Size = 0.014 inches

Figure 6-22

2. Operating Stress Required for Crack Growth: The results from the NASGRO analysis for the minimum flaw size for crack growth at max power were extrapolated to relate smaller flaw sizes to the operating stress necessary for propagation (see Figure 6-23). The operating stress required for growth of the 95% flaw was derived from this curve and found to be 52 KSI. Therefore, any engine operating condition that produces an operating stress greater than 52 KSI can be expected to cause a 95% flaw to propagate. Note that this stress is lower than that required for propagation of the minimum flaw in both the TIO and IO engine models.

Figure 6-23


Required crack size for crack growth
Largest Defect seen, .021in.
Estimated 95% Probability Defect .014 in
IO Min Flaw Size (0.0104 in.)
Above the Curve, the Crack will Grow
TIO Min Flaw Size (0.0054 in)
Below Curve, Crack won't grow
Estimated 50% Probability Defect .006 in
Crack size, 2a, Inches
0.025
0.02
0.015
0.01
0.005
0
45
50
55
60
65
70
75
80
85
Max Stress, KSI

3. Operating Stresses For Typical Flight Profiles: Operating stresses at the critical subsurface location for the varying power levels encountered during typical flights were extrapolated from the Stress Recovery results by using Brake Mean Effective Pressure (BMEP) in the cylinders for a given horsepower (see Figure 6-24). It's important to note that both TIO engine models operate at or above the minimum stress necessary for propagation of the 95% flaw for most portions of the typical flight, but the IO only operates at or above that stress level for a short duration during the initial takeoff roll. Therefore, the TIO will accumulate a much greater number of potentially damaging stress cycles per flight than the IO.

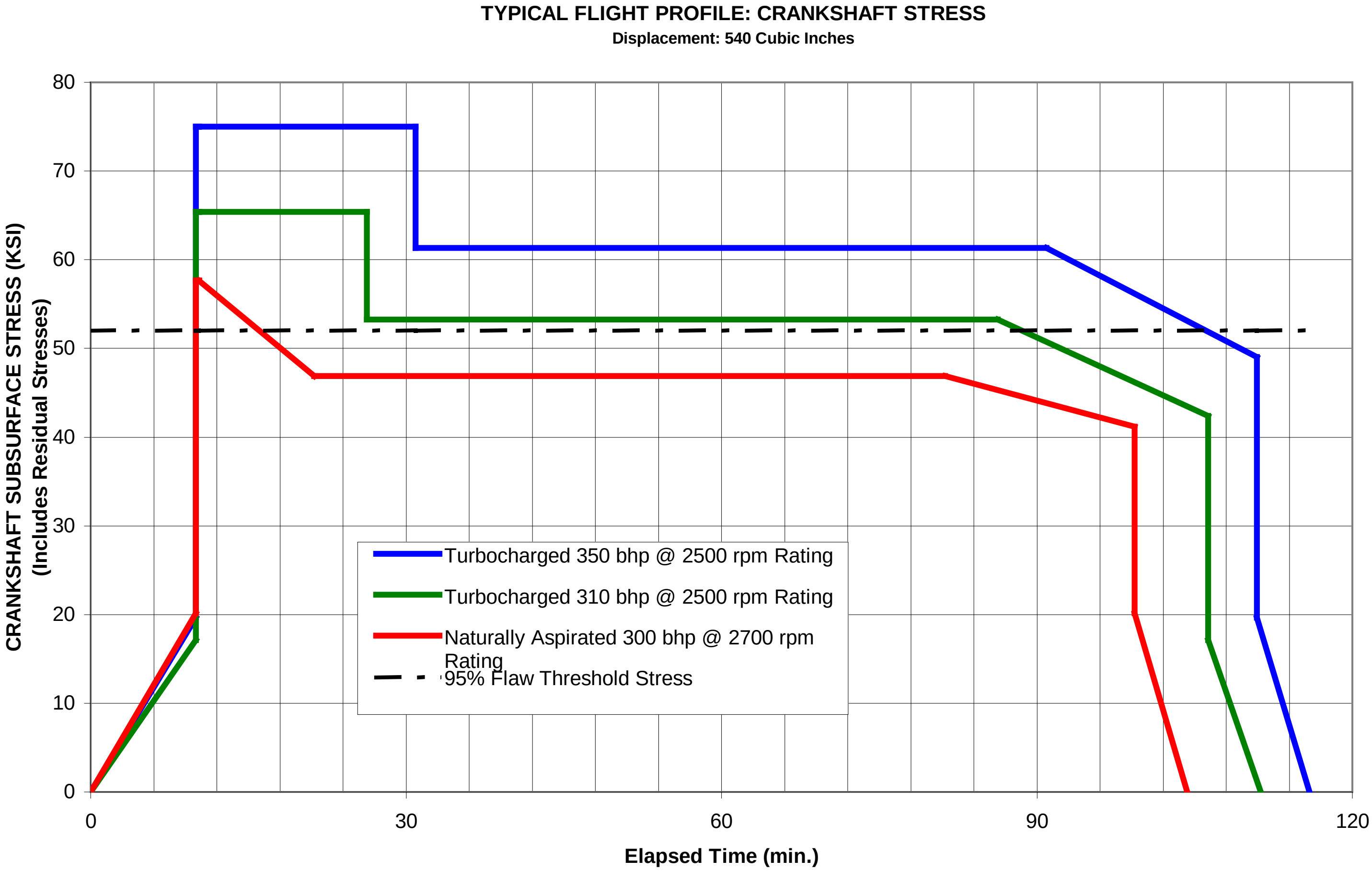


Figure 6-24

Operating stresses at the critical subsurface location for the power levels encountered during the FAR 33.49 150 hour engine endurance test were also plotted in a similar manner (see Figure 6-25). In this case, both the TIO and IO operate above the minimum stress necessary for propagation of the 95% flaw for most portions of the test. The stress levels produced by both engines are similar because the uninstalled, sea level standard day test conditions minimize the benefit of turbocharging to a large degree.

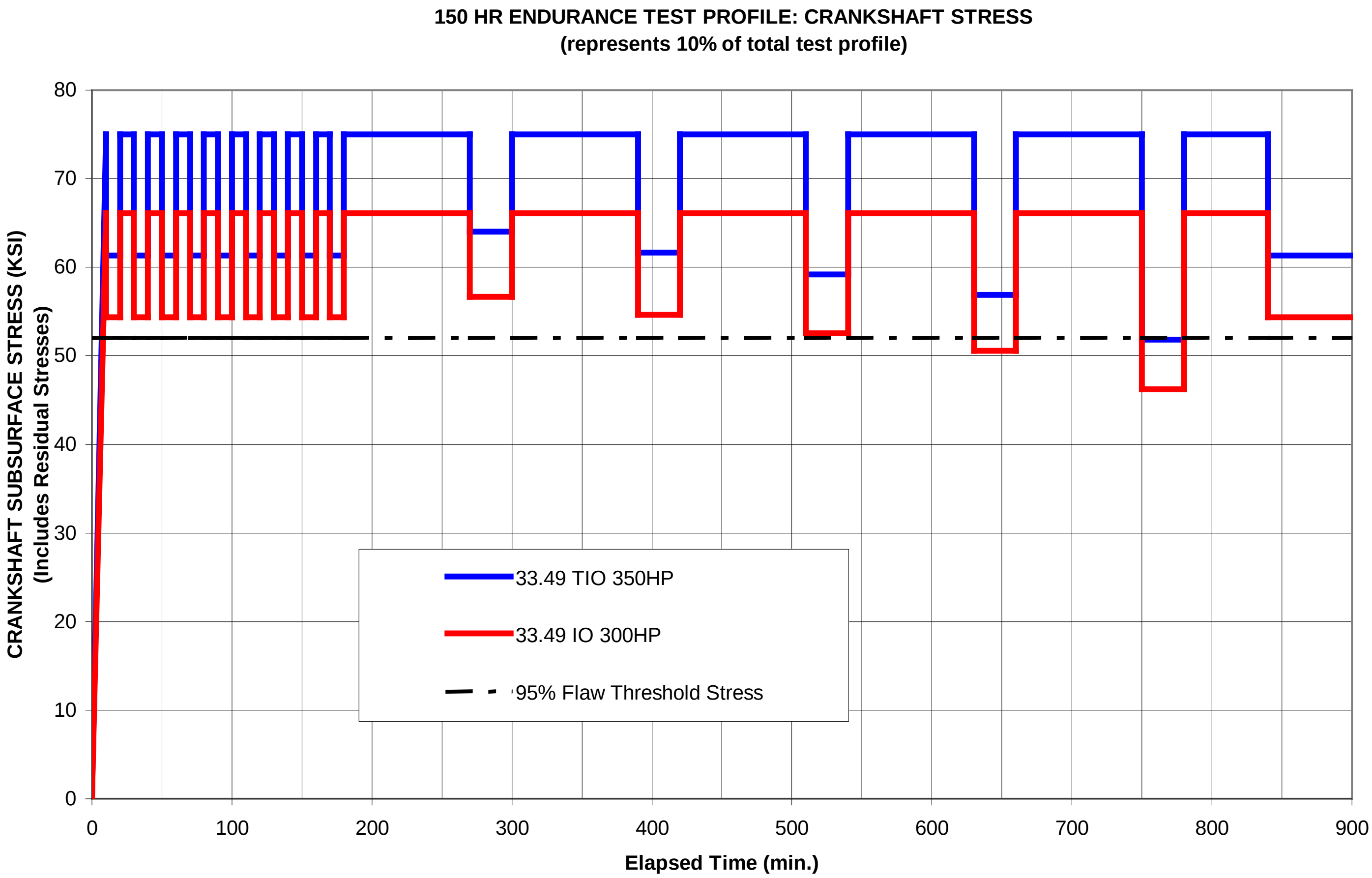


Figure 6-25

vi. Honeycomb Crankshaft Service Life Assessment

An estimated number of flight hours until crankshaft failure for those shafts with a 95% flaw was derived from the damaging stress cycle rate per flight and the service experience of the TIO-540 engines (see Figure 6-26). Given the worst-case failure time of 100 hours for the TIO crankshaft, the total number of cycles to failure was derived from the typical mission profile and found to be approximately 6 million cycles. Only cycles at power levels that produce operating stresses greater than that required to propagate the 95% flaw were counted. These cycles were called “damaging cycles”. The damaging cycle/hour rate for the IO flight profile was then evaluated to determine the range of flight hours required to accumulate the assumed 6 million cycle “life”. This “most severe flight profile” rate resulted in a worst-case IO crankshaft life of approximately 1500 hours. It should be noted that the IO damaging cycle per hour rate is believed to be extremely conservative because environmental conditions (altitude & temperature) will limit most IO engines to operation below the 95% flaw operating stress at all times and therefore would never generate operating stresses necessary to propagate the 95% flaw. The remaining 5% of crankshaft flaws (95-100 percentile flaws) would propagate at lower stress levels if the flaw was the proper orientation but still should only experience stresses high enough to propagate cracks during a limited portion of each flight. Based on expected damaging cycles accumulated per flight and service experience to date, it is believed that IO crankshafts will operate safely beyond the first TBO of 1600 to 2000 hours. However, beyond the first TBO, the combinations of flaw size, flaw location, material endurance limit, engine rating, and operating environment variables make it impossible to accurately predict how many additional overhauls any suspect IO shafts could remain in service.

The damaging cycle per hour rate from the 150 hr endurance test profiles for the TIO and IO was also compared to the 6 million cycle life. It was revealed that both the TIO and IO engine models would accumulate this number of cycles in almost the same number of test hours; 83 hours for the TIO and 86 hours for the IO.

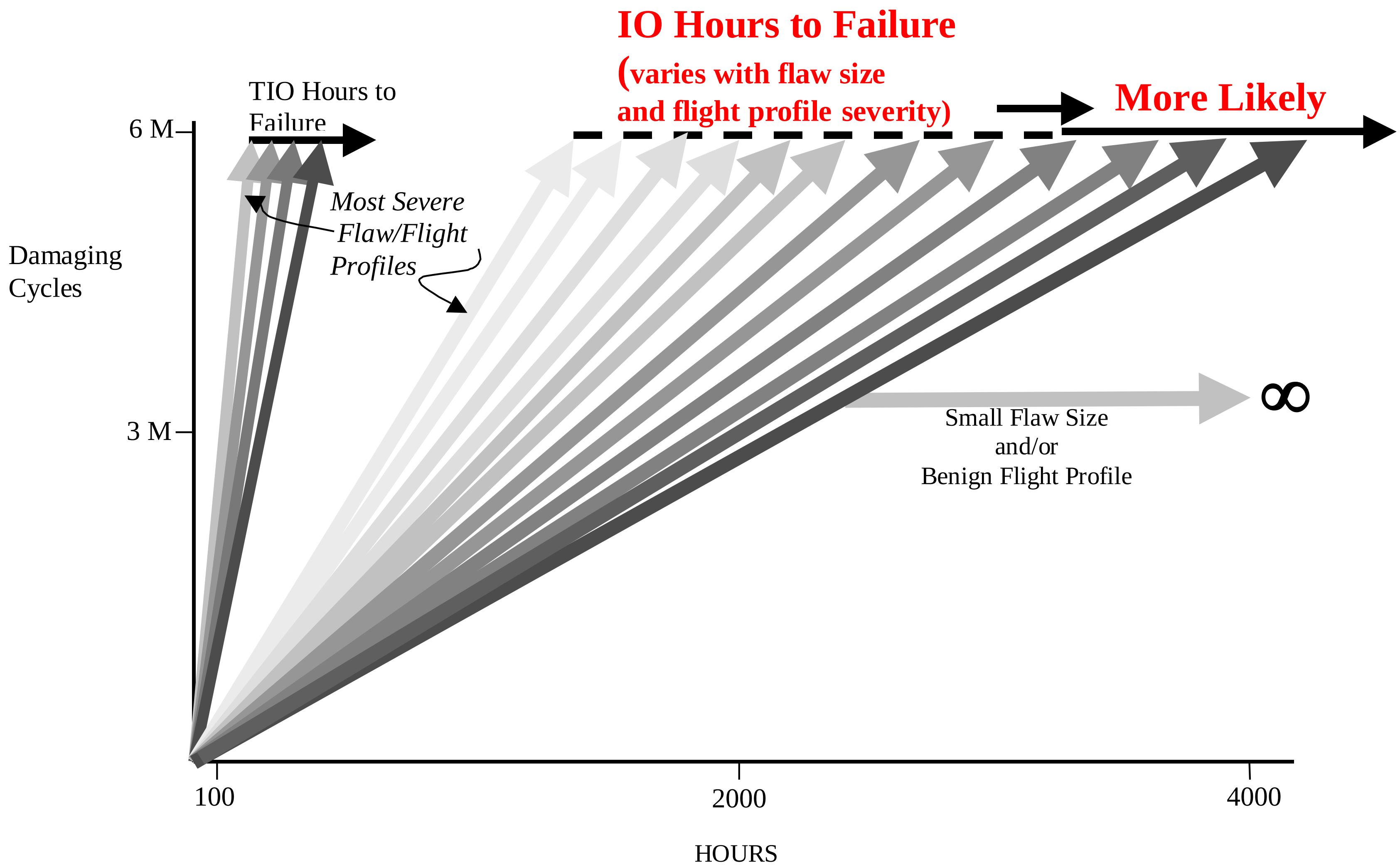


Figure 6-26
Service Life Assessment

LESSONS LEARNED

a. Crankshaft Fatigue Life: The crankshaft has a sufficient design margin between operating stresses and material endurance limit to result in an effectively infinite service life for defect-free material when installed in either the TIO-540 or IO-540 engines. The geometry and materials specified in the crankshaft design definition are adequate for the current operating loads.

b. Propagation of Flaws: Crankshaft operating loads are sufficient to propagate typical flaws associated with the honeycomb feature.

c. Detectable Flaws: The subsurface threshold flaw size that can propagate under normal operational loads is too small to be detected with current NDI techniques.

d. Damaging Cycle Accumulation: TIO engine models accumulate damaging stress cycles at a much faster rate than IO engine models. Crankshafts with honeycomb features installed in TIO engines will most likely fail prior to the TBO of the engine, whereas crankshafts with honeycomb features installed in IO engine models could operate past TBO.

e. 150 Hour Endurance Test: The test profile of the 150 hour endurance test results in the accumulation of a sufficient number of crankshaft damaging stress cycles to propagate the 95% flaw. However, the 150 hour endurance test results in the accumulation of only 8 million stress cycles at max power, which is less than the 10 million max stress cycles associated with infinite fatigue life.

RECOMMENDATIONS

a. Subsurface Flaw Inspection: Flaws of the threshold size are not detectable with conventional NDI technology. Therefore, screening of crankshafts and crankshaft material during production for indicators of existing flaws (such as honeycomb), and controlling material properties during manufacture is necessary to prevent in-service crankshaft failures.

b. Crankshafts Installed in IO Engines: A service program should be developed for crankshafts installed in IO engines that either establishes a honeycomb screening inspection or a remove and replace schedule to minimize the probability of in-service failures.

c. Substantiation of Crankshaft Major Material, Process or Supplier Changes: Durability testing beyond the 150 hour endurance test should be performed to accumulate more than 10 million cycles at max power for qualification of major changes to crankshaft material, processes, or suppliers.

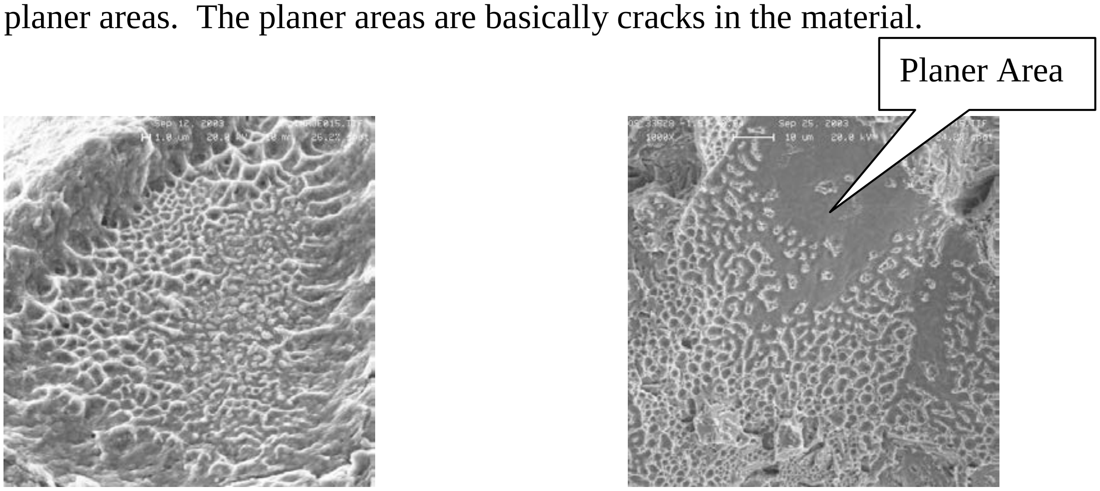
7. Metallurgical Working Group

The Metallurgical Working Group reviewed data and lab reports related to Lycoming's examination of crankshaft material, independent consultant's examination of crankshaft specimens, and performed their own independent exam and fatigue testing of crankshaft material. The primary objective of this group was to investigate the honeycomb feature, determine how it is formed, and its impact on the material properties of the crankshaft.

INVESTIGATION

a. What is the Honeycomb feature and how is it Formed?

"Honeycomb Feature" is a term used first by Teledyne Continental Motors to describe a feature found on a fracture surface created by impact fracture of a Charpy Specimen. It is believed to be the result of alloying elements and contaminants segregating to the grain boundaries during forging when the crankshaft is forged at excessively high temperatures as the grain boundary begins to melt. In extreme cases, the honeycomb feature can have a planer appearance in the center and the feature size is larger (see Figure 7-1). This is believed to be an indication of more excessive overheating and/or tensile strain during forging. In the photographs below, the picture without the planer features is about 5 times the magnification of the photo with the planer areas. It is believed that as the degree of overheating increases, the honeycomb feature evident on the Charpy Specimen will be larger and will begin to form planer areas. The planer areas are basically cracks in the material.



Honeycomb feature Without Planer Areas | **Honeycomb feature Areas with Planer Areas**

Figure 7-1

We believe excessively high temperatures used during forging at Interstate form the honeycomb feature. Two studies have been done to confirm this, one by Dr. Hinton for Standard Steel in the context of defending Standard Steel against litigation following failures of Continental engines in which the honeycomb feature was found[2]. Another study was also done by Dr. Hinton for Lycoming in the context of the present investigation[3]. Dr. Hinton's data in the Lycoming study indicates was that the feature can be formed when the steel is forged above 2550 degrees. It also indicates that, at least up to 2610 degrees F, the feature won't form if the steel is not forged. This means that forging, and probably a tension stress during forging are necessary conditions for honeycomb formation and for the resultant microcracks.

Dr. Hinton's study did not investigate the degree of plastic deformation required to form the feature, or other possible forging variables, so it is possible that the 2550 cutoff may not be completely representative of the real crankshaft manufacturing processes. In addition, there may be some variability inherent in the steel and forging design that might influence this temperature to a limited extent.

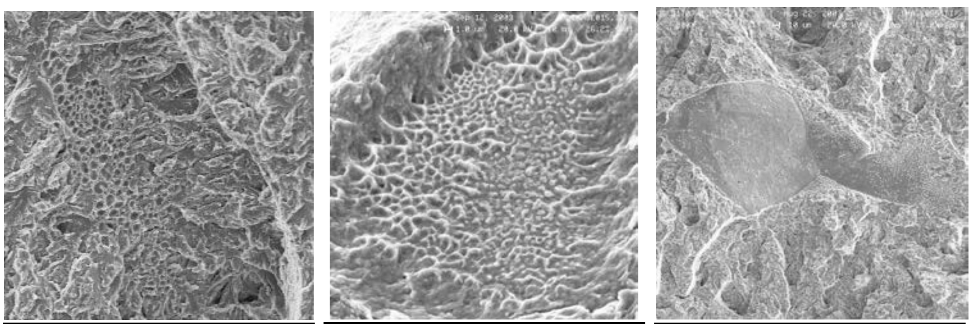
Lycoming's process specification set the maximum forging temperature at 2350 F. It is unlikely that the honeycomb feature would have formed if the forging had been done accordance with the Lycoming specification requirements. The aerospace metals handbook lists the melting temperature range for 4335 Vanadium modified as 2645 to 2845 F and the melting point of 4340 as 2740 F. Another phase of iron called δ ferrite forms above the temperature range for austenite, but below the melting point that can cause problems. In this steel, the delta ferrite range is about 150 deg F. Based on these ranges, we would therefore expect that we have about a 150 deg F margin above the specification range before incipient melting occurs, even with vanadium present.

Large forging tend to increase in temperature during forging due the energy imparted to them during plastic deformation. No hard data is available for the magnitude in the case of the Lycoming crankshafts, but 100 degree F temperature rise has been seen in other similar forgings. This means that our actual temperature margin could be as low as 50 deg F.

Based on extensive examination with the scanning Electron microscope during the FAA evaluation, the team reached the conclusion that the formation of the

[2] Hinton, R. W., Report No. 131-Teledyne vs. Standard Steel Summary Report, March 9, 2002
[3] Hinton, R. W., Report 101-JDRP-Tabulation of Forging Study results, July 24, 2003

honeycomb feature can vary in degrees (see Figure 7-2). Mild overheating and/or small amounts of hot working producing tensile stresses during forging appear to produce small honeycomb features that do not have microcracks when only a portion of an occasional grain boundary was affected. Medium levels of overheat and/or tension stresses during hot working appear to cause most of one facet to form the cellular structure referred to as honeycomb and they tend to be larger. High degrees of overheat and tension stresses during overheat cause the honeycomb feature to disbond along the grain boundary and cause a microcrack.



Mild Overheat/Hot Work Small without planer areas	Medium Overheat/Hot Work Most of a facet, beginning to form planer areas	Severe Overheat/Hot Work Multiple grain facets, planer areas

Figure 7-2

b. What is the microcrack and how is it related to Honeycomb?

i. Microcrack Formation

The microcrack is the result of the honeycomb feature maturing during the forging process to the point where the entire prior austenite grain boundary looses all it’s ability to sustain tension loads and becomes a crack. This is shown in the severe overheat/hot work picture of Figure 7-2. This can also be seen in metalographic sections examined during investigation of crankshaft service failures (see Figure 7-3). This failure is from a TIO 540 J2BD engine with the large journals. The crankshaft failed after 921.3 hours. The crack was found in the same area as the failure, but because it was a little smaller and not in as high stress an area of the crankshaft, it didn’t grow. Figure 7-4 is a magnification of the crack shown in Figure 7-3 and shows how the crack develops out of the honeycomb feature. The length of this crack was measured to be .007 inches in this view, but because it is a section cut through the shaft, it is almost certainly larger in the body of the material.

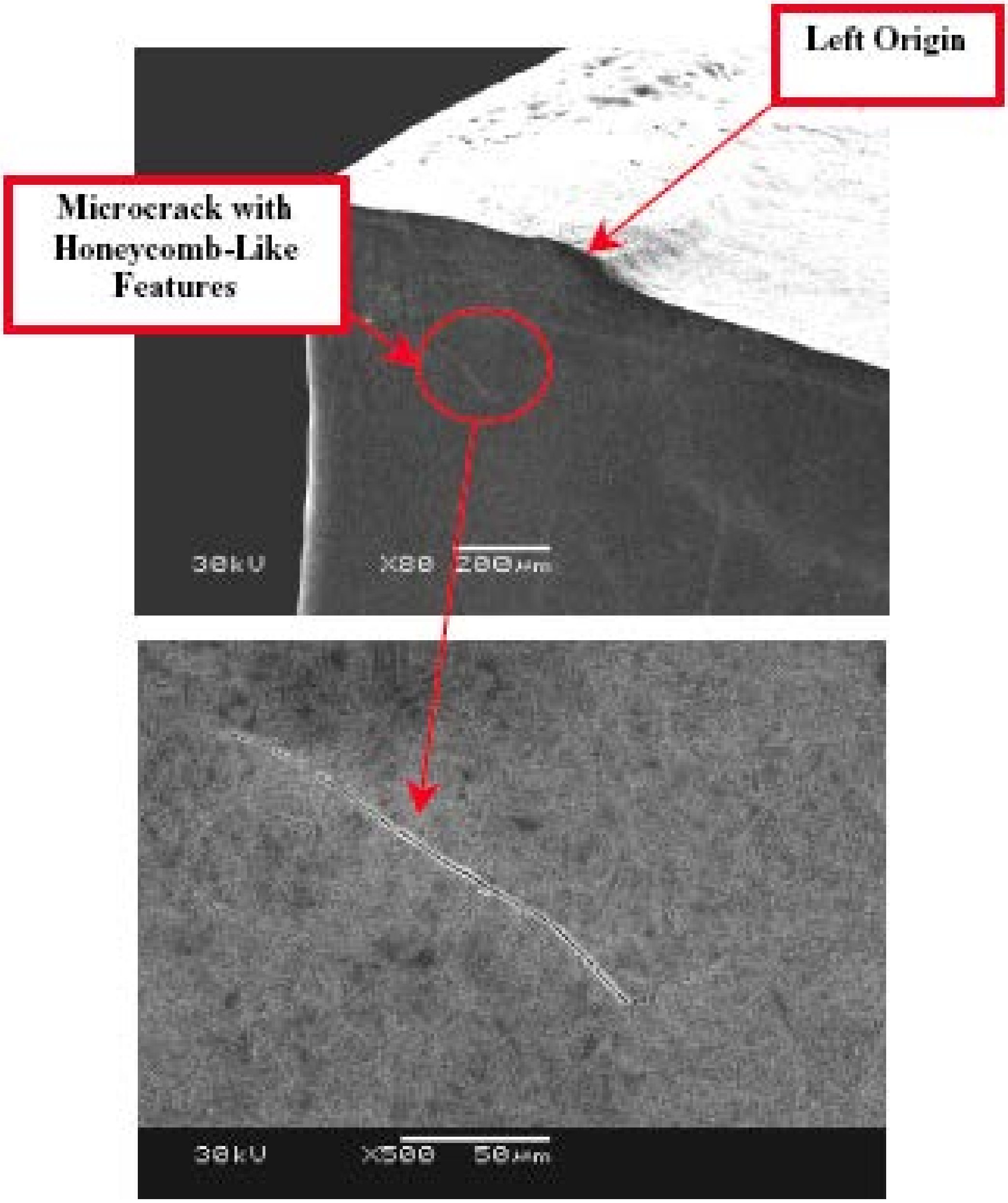

Left Origin
Microcrack with Honeycomb-Like Features
30kU
X80
200µm
30kU
X500
50µm

Figure 7-3

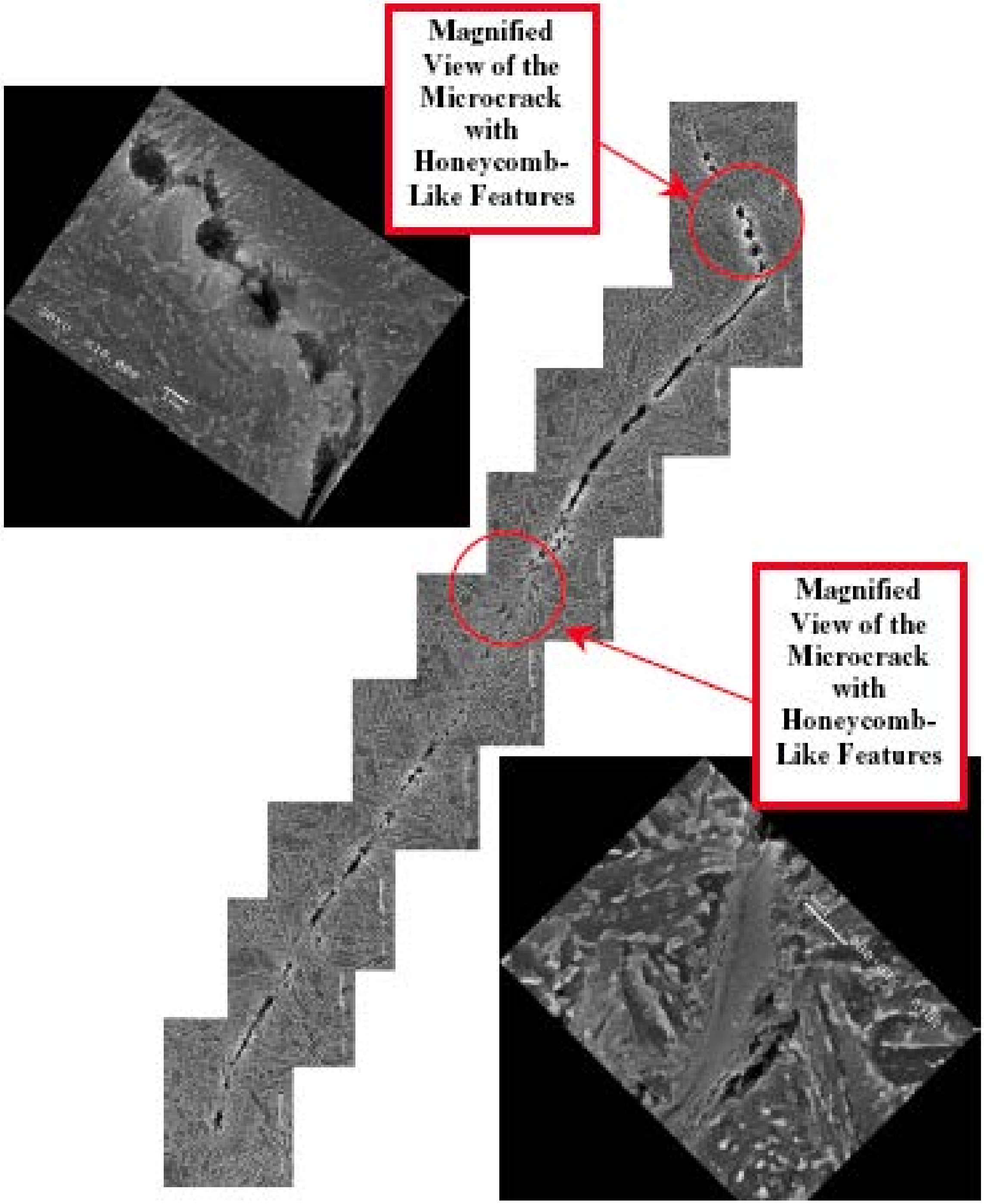

Magnified View of the Microcrack with Honeycomb-Like Features
Magnified View of the Microcrack with Honeycomb-Like Features

Figure 7-4

It is believed that the microcrack forms in the following sequence of events:

- Overheating the billet prior to forging allows the grain boundaries to soften to a nearly molten state.
- When the forging dies close, the metal flows into the cavities in the die, and in certain areas, most importantly in the crank pin journal radiuses; the nearly molten material is in tension as it expands into the crossover cheek cavity.
- The tension stress applied to the grain boundary exceeds that ability of the almost liquid material to hold together, and the grain boundary breaks.

This phenomenon has been compared to what would happen if you put glue between two pieces of cardboard, and before the glue was dry, pulled the cardboard apart. The pocked surface left by the glue is analogous to the surface seen the SEM in the honeycomb areas.

The FAA independent investigation determined that the honeycomb feature is not uniformly distributed based on cutting up the crankshaft in several locations and conducting Charpy and fatigue tests. Based on the somewhat limited data we have, the microcrack appears to be more likely to exist in the critical radius, than in the straight portion of the shaft under the main bearing at the prop end of the shaft, probably due to the tension stresses that probably exist in that area during forging. The microcharpys that are taken in the prop flange area may have a tension stress during forging as well, and therefore may still be an acceptable location to detect the presence of microcracks and the honeycomb feature.

Because the forging grain flow is going straight under the front main bearing, there are minimal forging tension stresses. In the crossover cheek, as the material is flowing from the number 5 to the number 6 journal, and has to expand into the crossover cheek during forging, producing tension stresses. This produces the honeycomb feature and the microcrack if the forging is overheated (see Figure 7-4a).

Data from examination of specimens taken out of suspect crankshafts in many locations during the FAA investigation at Seal Beach indicates that the defect is more likely to occur in areas of tensile stress during forging, so the prop flange samples may not be representative of the defect population at the critical location

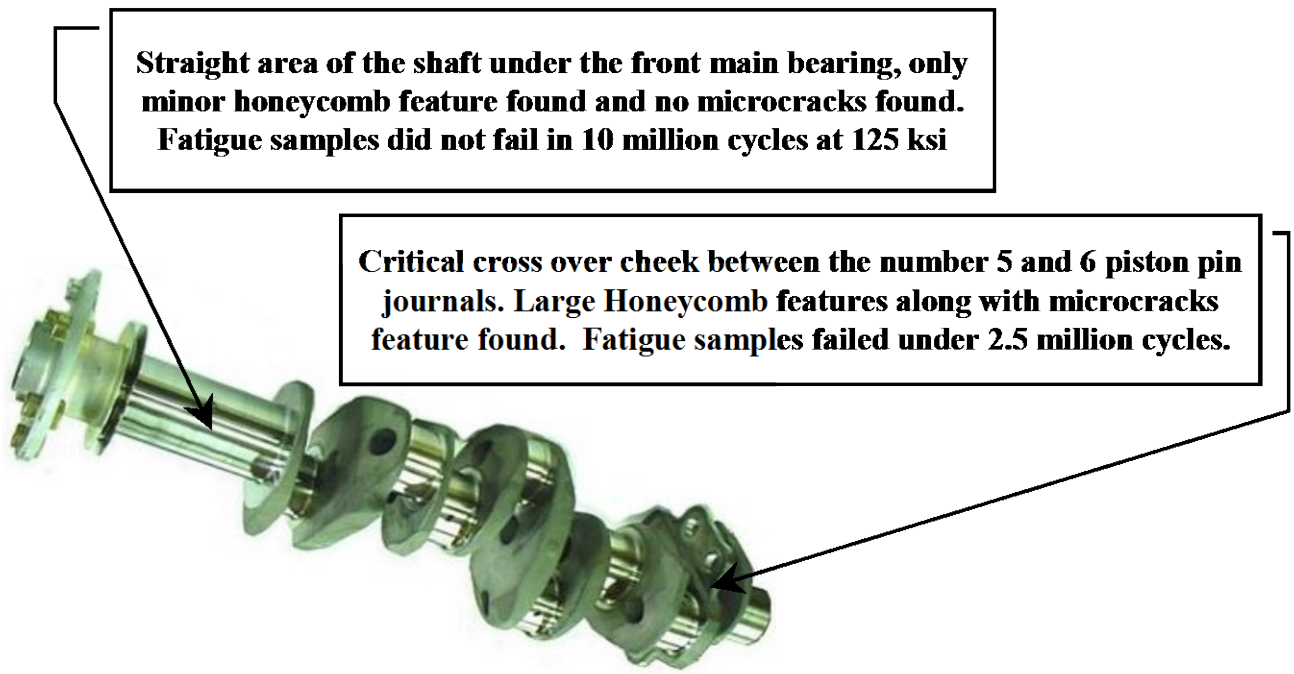


Figure 7-4a
Distribution Within the Crankshaft of Honeycomb and Microcracks

ii. How Large is the Microcrack?

We have several available estimates for the size and distribution of the microcrack size.

- The size observed in the two actual failed crankshafts that had an undamaged fatigue origin. The first one was .0093 and the second one had two origins in close proximity, one was .005 and the other was .008 inches.
- The estimated 95 percentile crack size observed in Scanning Electron microscope images taken for a variety of sources is .014 inch.
- From a Lycoming study of the size of the honeycomb feature in a random selection of crankshafts in the affected heat lots but that had not failed reveals that 5% of samples taken from the prop flange have a defect of .008 inches or larger. (other data from examination of specimens during the FAA investigation at Seal Beach indicates that the defect is more likely to occur in areas of tensile stress during forging, so the prop flange samples may not be representative of the defect population at the critical location)

We believe that our best estimate indicates that the microcrack average size is about .006 inches, and the 95% probability defect size is .014 inches. The largest microcrack seen so far is .021 inches. The following describes how we know what we know about the sizes of defects.

1. <u>Analysis of Scanning Electron Microscope photographs</u>.

Through the course of the investigation, many samples have been examined in the scanning electron microscope. Photos of the defects found have been taken with the magnification noted. These photos were used to establish an equivalent microcrack size. The longest dimension of the crack up to the edge where normal fracture is seen was used as the length. Most of the cracks were not circular in appearance. Figure 7-4b shows an example of how this was done.

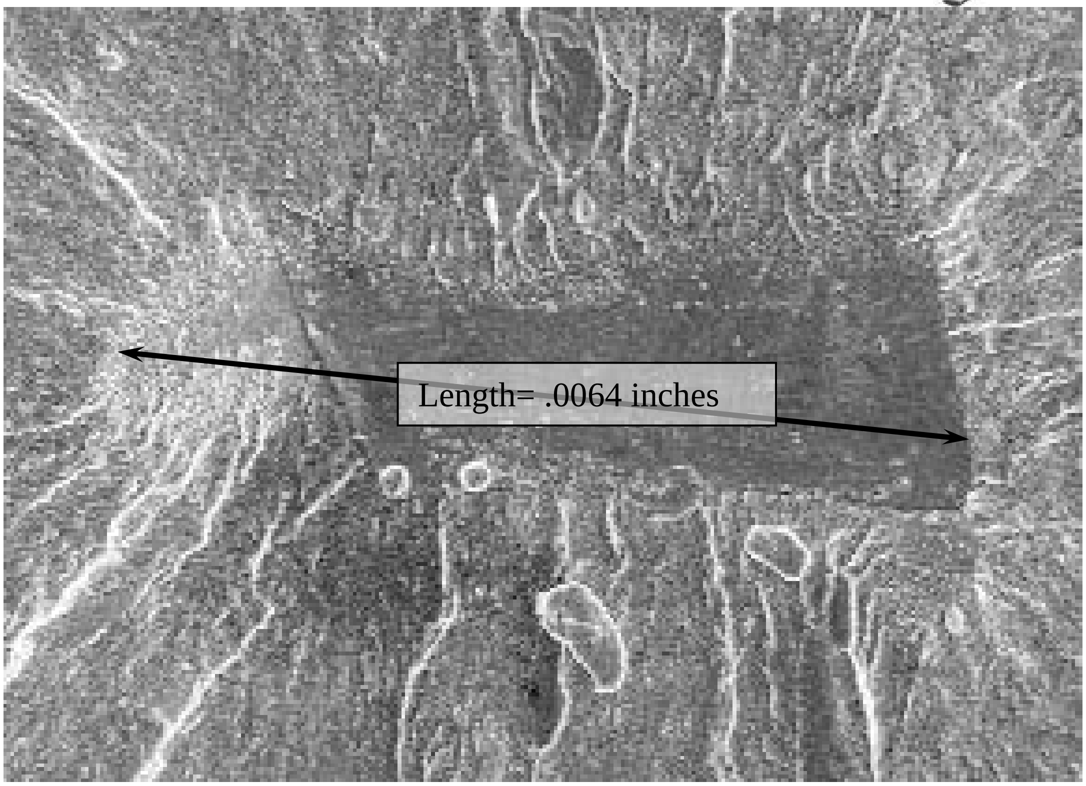
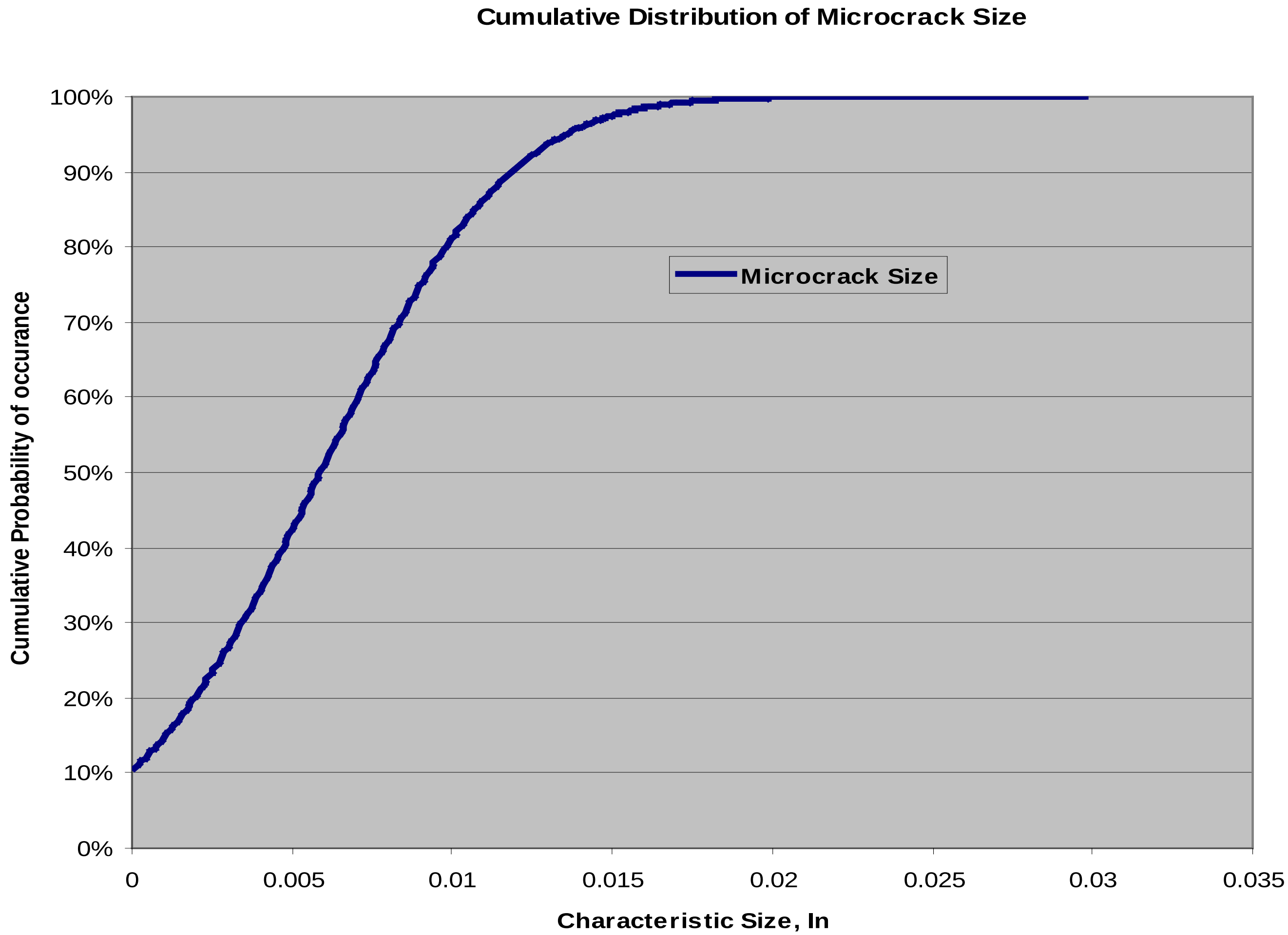


Figure 7-4b Aproximate 50% defect found by Dr. Barsom in a fatigue test specimen extracted from a crankshaft in the affected heat lot.

The data from the examination of SEM photos of microcracks was used to develop the cumulative probability distribution of microcrack size presented in Figure 7-5. The curve crosses the 50% line at .006 inches and crosses 95% at .014 inch.

There is an inherent bias in the data shown because the collection of the photographs was not done in an attempt to quantitatively describe the distribution of micro cracks, rather it was an attempt by various individuals, FAA investigators, Dr. John Barsom, consultant to Lycoming, and others to document their findings on a variety of ways.

Figure 7-5, Cumulative Distribution of flaw sizes from study of cracks observed in SEM



2. Photographs of the initial defects found during failure analysis of the Crankshafts.

A clear fracture origin was found in the crankshaft that failed in a Piper Navajo that failed in July of 2001. The size of the initial defect was .0093 inches (see Figure 7-6). According the Figure 7-5 above, this represents a 77% probability of occurrence. This crankshaft failed at 887 hours at the number 6 connecting rod journal, which, according to the stress analysis by LMS, has a lower stress than the number 5 connecting rod journal by about 10.5%. Figure 7-6a shows the origins of the other crankshaft that had a clean origin. The left origin was .008 and the right was .005 inch.

At the stress level indicated, the required flaw size for propagation in this engine at this location and at this power is .0070 in. Since this flaw obviously did propagate to failure in 887 hours, the conclusion that the SCRT Team reaches is that the fracture mechanics analysis is quite accurate in this case.

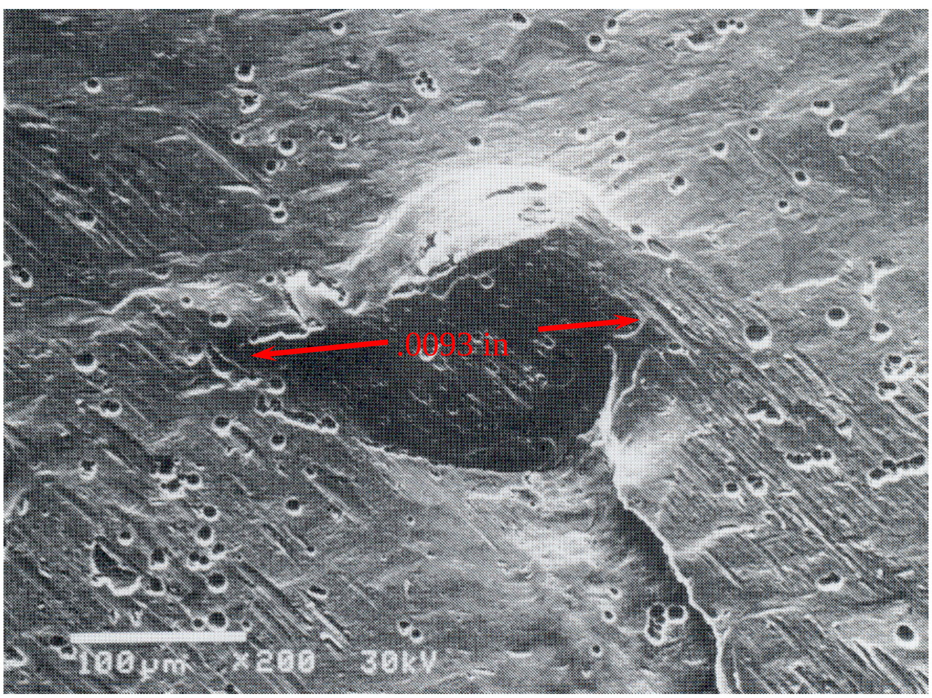


Figure 7-6. Flaw found in the number 6 journal in TIO 540J2BD, heat code SS-9T installed Piper Navajo. Failure was at 887 hours. Large Main Crank operating at 350 hp.

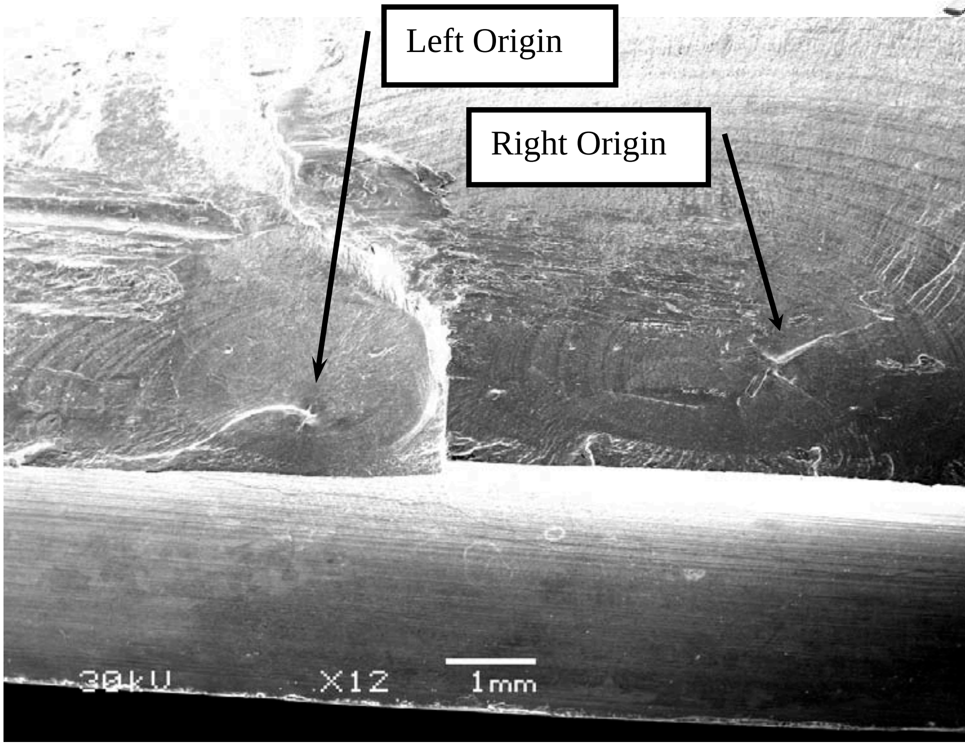


Figure 7-6a, Taken from the failure analysis of failed crankshaft showing multiple origins.

3. <u>Lycoming random samples taken from the prop flanges of field returned shafts.</u>

Lycoming conducted a study of Micro Charpy samples taken from the prop flange of affected crankshafts. The Micro Charpy samples are .25 inch in diameter with a notch .080 inches deep. The result is that they are relatively small in cross sectional area, but the same order of magnitude as the area that is in the highly stressed area of the number 5 or number 6 crankshaft journal.

These data show us the defect size distribution in the prop flange area, and also give us some indication of the number of defects in a given square cross section. Figure 7-8 presents the data from that study for honeycomb feature size. It shows us that about 5% of the samples taken have a honeycomb feature size larger than .008 inches. Lycoming did not capture the distribution of the sizes within this part of the population; just that the minimum size in this range was .008 inch.

It shows us that the largest number of defects is in the .001 to .003 inch range. Based on the results of the fracture mechanics analysis, these defects are probably not large enough to propagate unless more than one of them are in the same area. This possibility brings us to the other data available in the Lycoming study. Because we know the number of defects per sample and the sample cross sectional area, we can calculate the number of defects per square inch. These data are presented in Figure 7-7.

From Figure 7-7 we can see that the data are roughly distributed in 1/3 increment with about a third of the population having more than 280 defects per square inch. This means that the chances that two defects are adjacent are quite real. This is supported by the failure of V537912980 where an examination of the fatigue origin revealed two defects, and a third below the surface of the fracture surface.

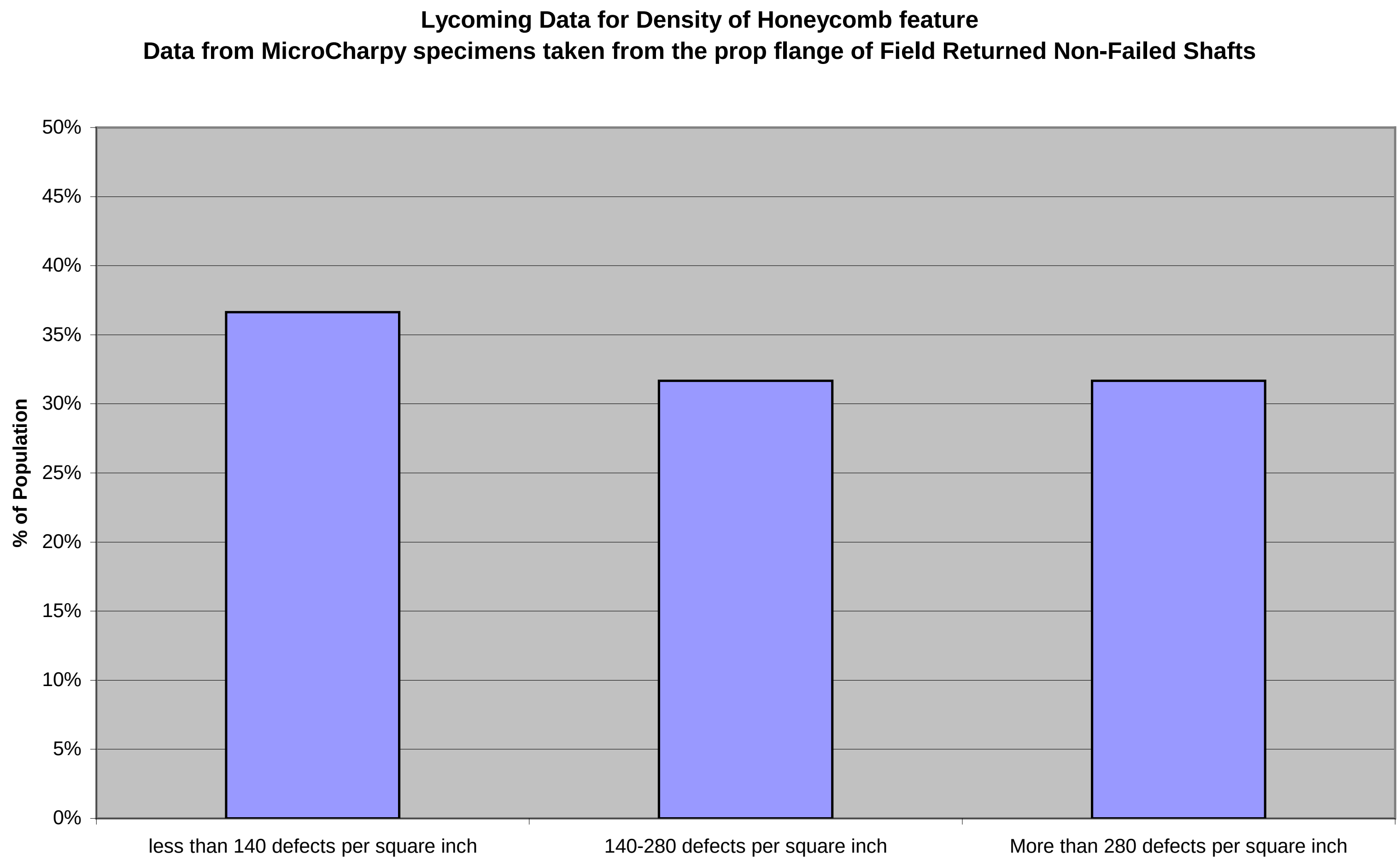


Figure 7-7. Density of Defects found in prop flange samples from Lycoming study

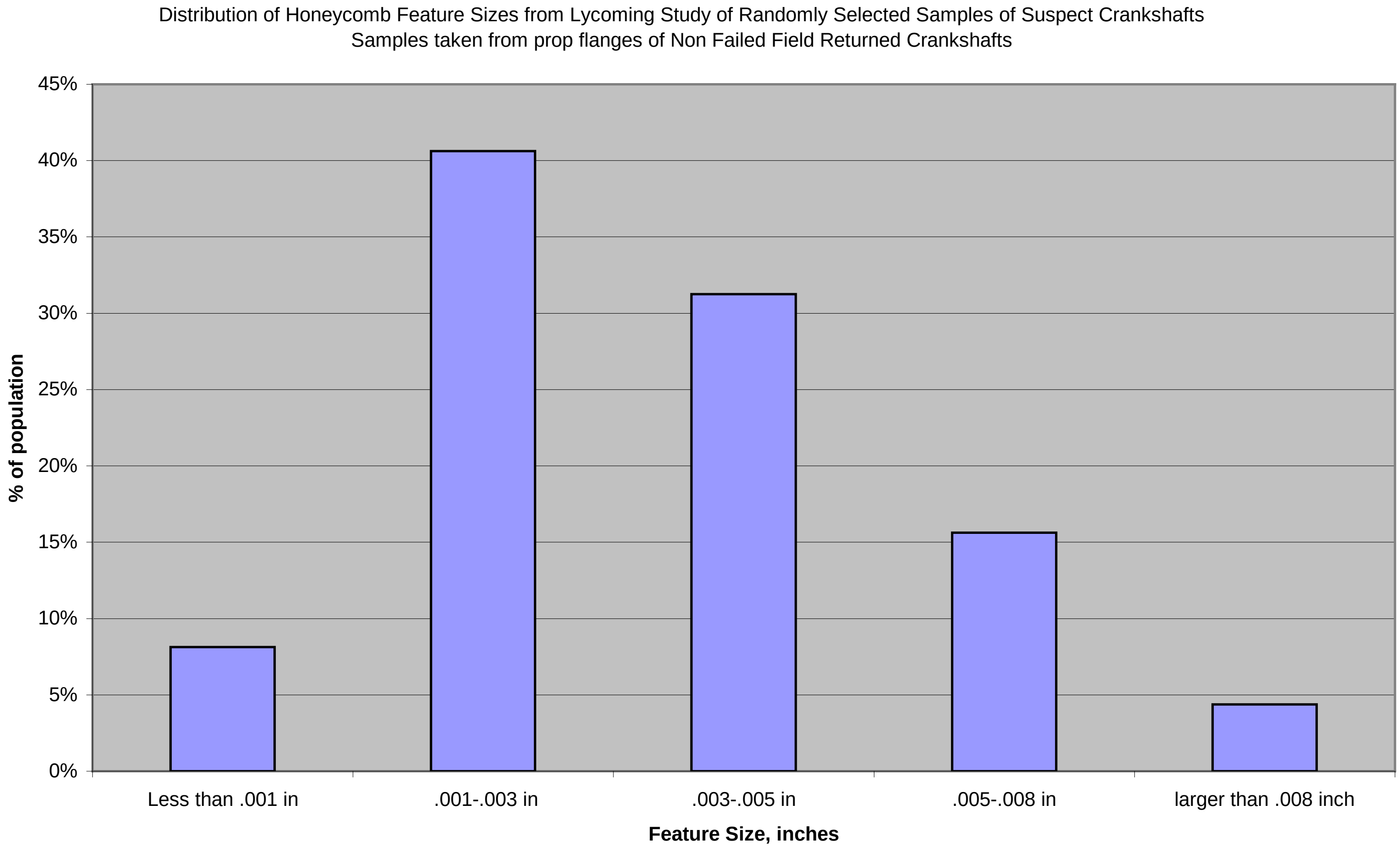


Figure 7-8. Distribution of defect sizes found in prop flange samples. Data from Lycoming study.

c Why do Crankshafts with Microcracks fail?

The effect of the microcrack on the fatigue life of the crankshaft was evaluated during the FAA independent investigation. This was necessary because, despite repeated suggestions from the SCRT, Lycoming did not do any fatigue testing to determine what the fatigue life of the materials they were using or the fatigue life of the material was in the presence of the microcracks.

The FAA team performed tension-tension fatigue testing on specimens from forgings produced by both Krup-Gerlach and Interstate. None of the samples tested from the Krupp shafts failed within 10 million cycles when tested at 125 KSI. About 1/3 of the valid Interstate specimens failed before 10 million cycles. This tells us that the endurance limit for properly processed vacuum arc remelted 4340 without the microcrack is above 125 ksi, but the presence of the defect lowers the endurance limit below 125 KSI.

Samples taken from failed crankshafts with honeycomb showed fatigue failure starting at subsurface microcracks. These samples were tested at 135 ksi alternating stress. Two specimens hit the runout at 10 million cycles. These specimens probably did not have internal defects and therefore indicate that an endurance limit of 135 ksi is possible in this material in the absence of internal defects. However, three specimens failed at 51,995, cycles 91,958 cycles, and 517,789 cycles respectively, with all of the origins at subsurface microcracks. This confirms that the honeycomb feature and associated microcracks have a significant impact on fatigue life.

Figures 7-9 through 7-17 provide photographs of test specimens from the FAA investigation.

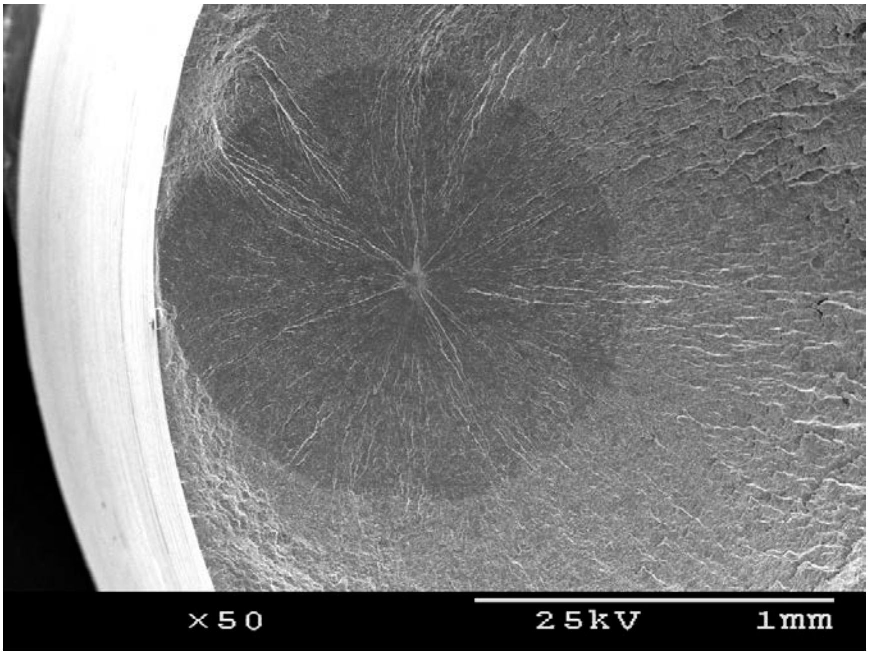


Figure 7-9 Photo taken from fatigue specimen IS-2. Specimen failed at 850,032 cycles. Specimen taken from the cross over cheek between the number 5 and 6 piston journals. Tested at 125 ksi alternating stress, R=.05, 10 Hz dry air. Note the subsurface origin at a microcrack

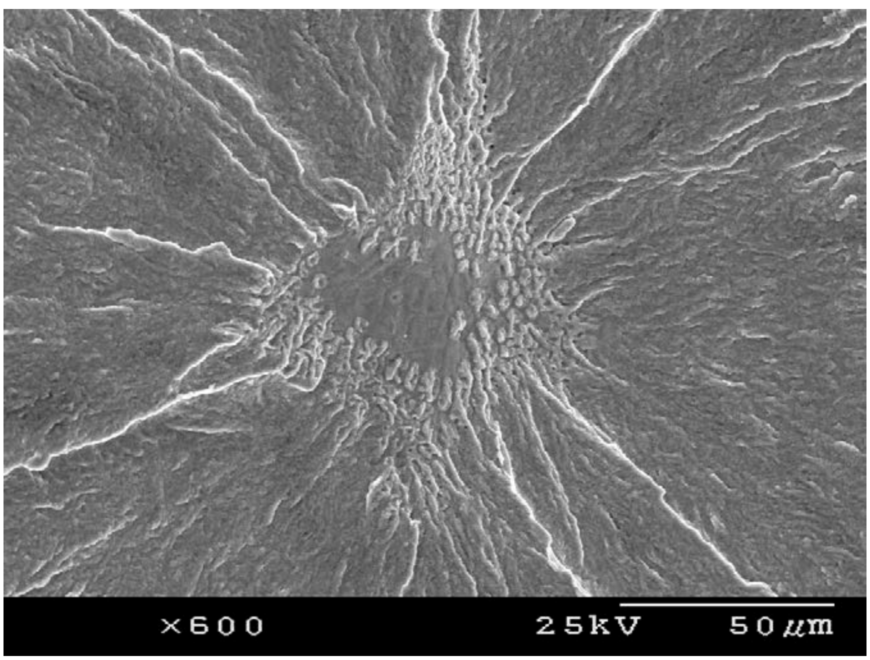


Figure 7-10 Photo taken from fatigue specimen IS-2 at the primary origin, higher magnification than figure 7-9. River marks indicate fatigue propogation from microcrack surounded by honeycomb feature. Specimen failed at 850,032 cycles.

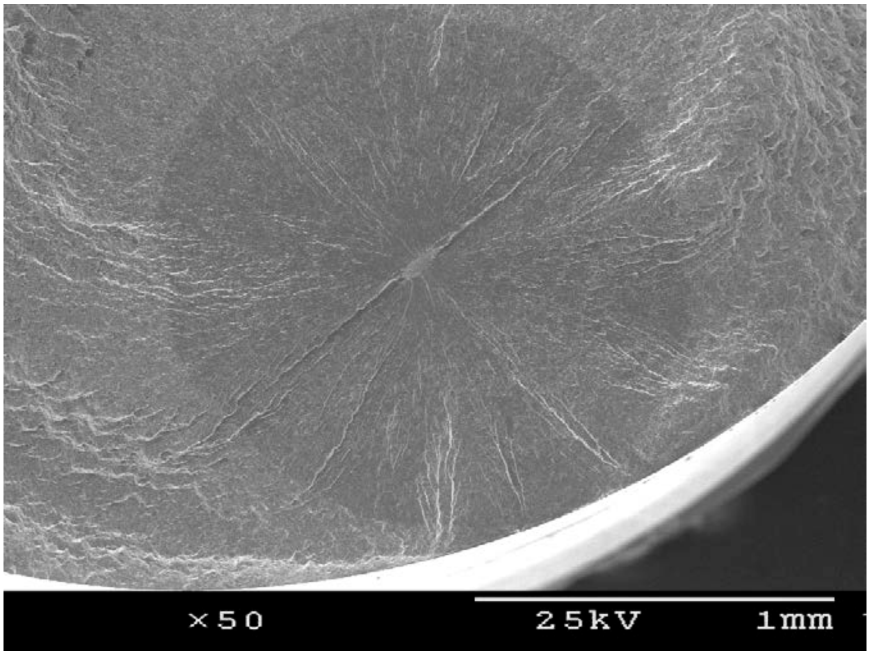


Figure 7-11 Photo taken of specimen IS6. Specimen removed from the number 5-6 cross over cheek. Specimen failed 2,190,571 cycles. Specimen tested at Tested at 125 ksi alternating stress, R=.05, 10 Hz dry air.

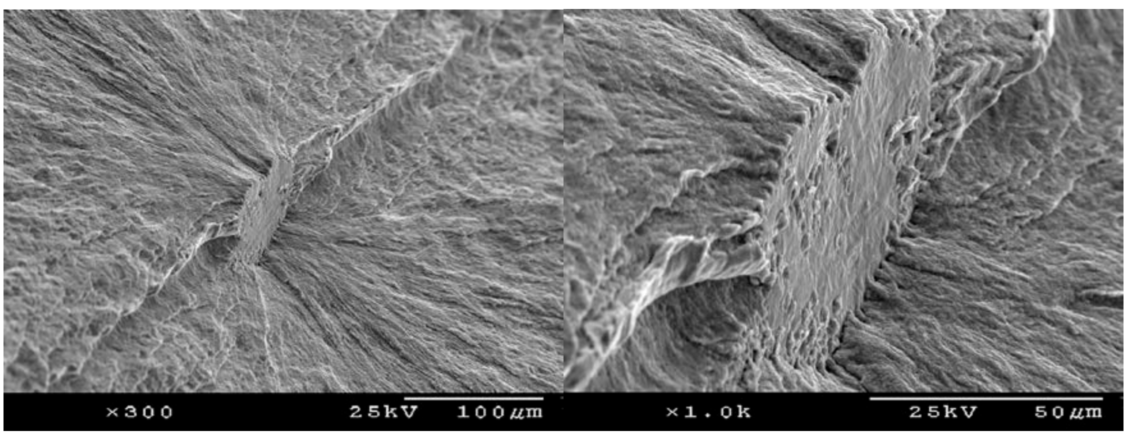


Figure 7-12 Increasing magnification pictures taken of specimen IS-6. This specimen was taken from the number 5-6 cross over cheek. The microcracks is inclined to the longintudinal axis of the specimen. Specimen failed at 2,190,571 cycles.

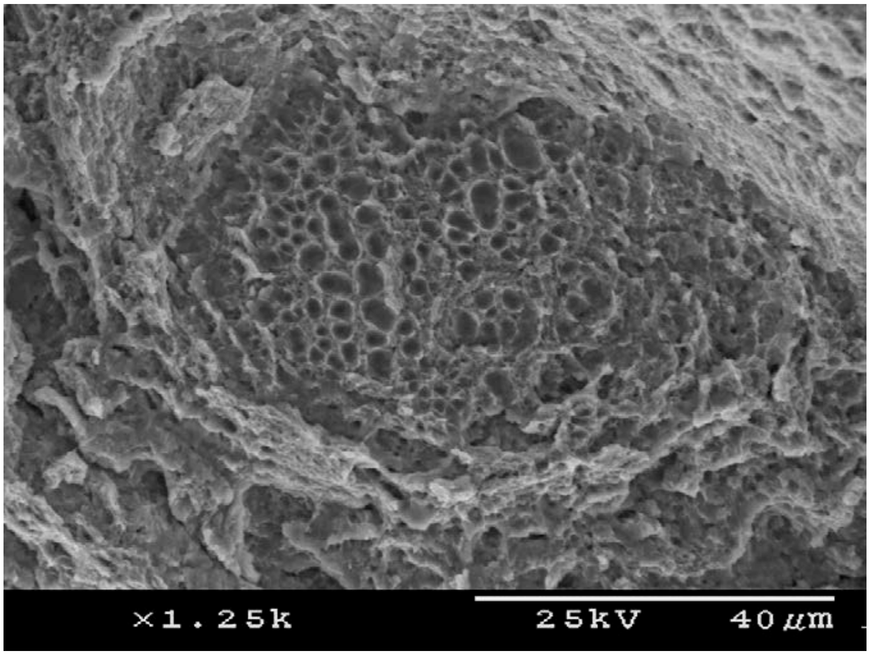


Figure 7-13 Honeycomb feature in specimen IS3 taken from a Charpy specimen taken from the number 5-6 crossover cheek.

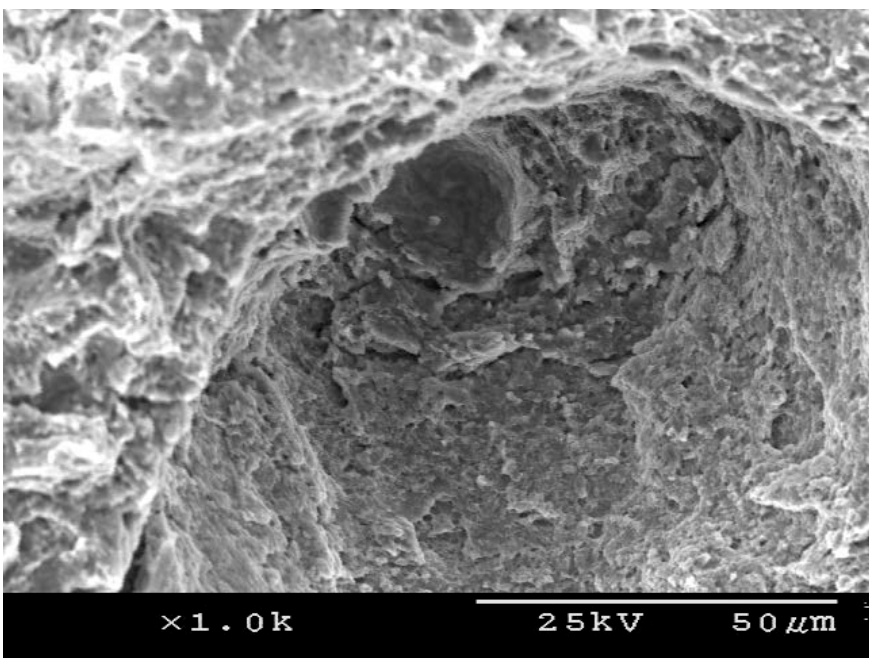


Figure 7-14 Pull out in Charpy specimen IS11 showing very small honeycomb feature at the bottom. Specimen taken from the interstate crankshaft under the forward main bearing. This was the largest feature found in this specimen.

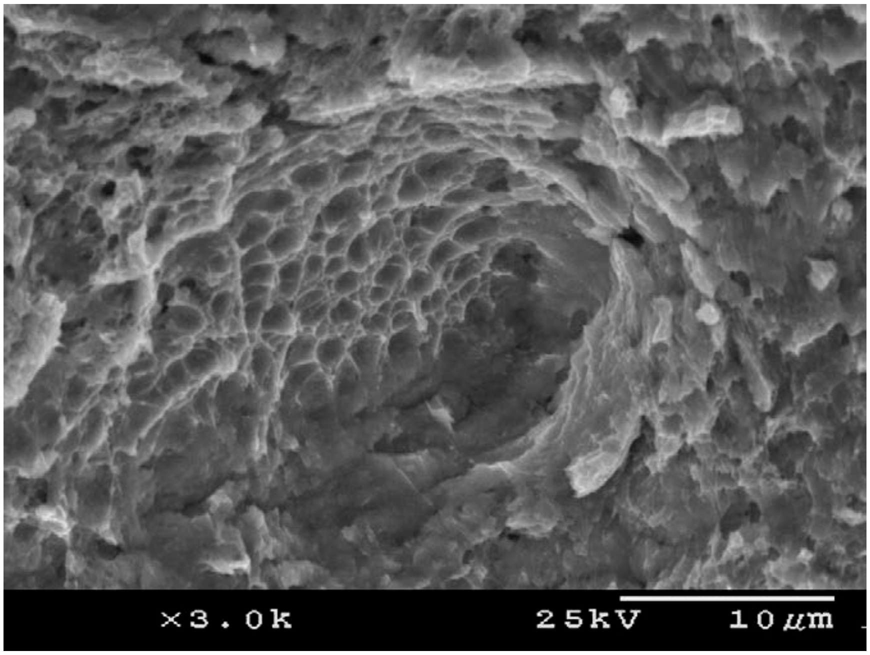


Figure 7-15 Small honeycomb feature found in Charpy specimen IS15 taken for an Interstate crankshaft in under the forward main bearing. This was the largest honeycomb feature found in this specimen.

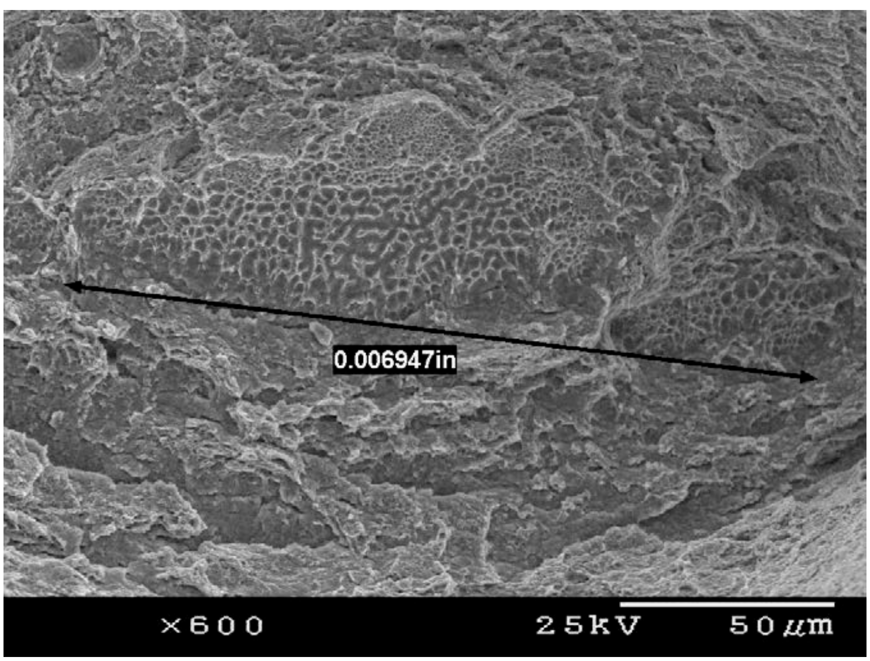


Figure 7-16 Largest honeycomb feature found is specimen IS7

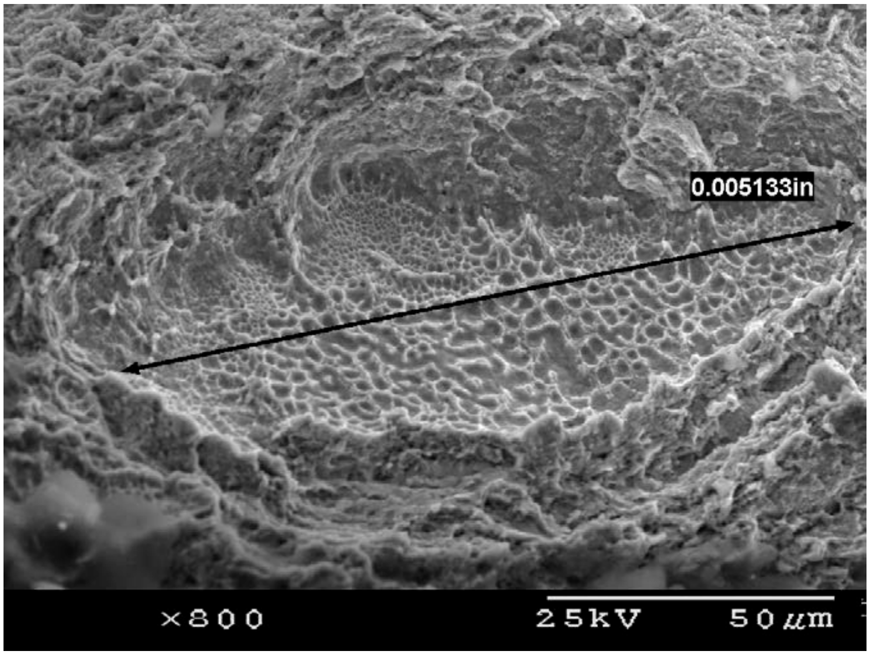


Figure 7-17 Picture from Charpy specimen IS 7 taken from to very close to the critical point in the number 5 crankshaft piston journal. Note the large size compared to those found under the forward main bearing where the grain flow is straight.

d. Why was this problem so difficult to identify?

The textbook method of determining overheat during forging has always been by metallographic section and looking for evidence of “burned” grain boundaries. Samples for the Lycoming and before them the Continental crankshafts did not show this phenomenon.

The following discussion is taken directly out of the 1939 metals handbook and remains virtually unchanged today[4].

> Burning is an extremely overheated condition, which causes the more fusible constituents of the steel to melt and run out into the grain boundaries and leave voids between the grains. Burning may occur in the heating furnace before any forging is done on the steel.

While photos were not reproduced in the 1939 versions, subsequent versions of the metals handbook show a characteristic pattern of the damaged grain boundaries as they melt and combine with the oxygen and sulfur in the steel as described above. It should be remembered that typically large forgings like crankshafts increase in temperature, sometimes up to 100 degrees F during the forging process due the energy imparted to them by the hot working.

In the mid 1970’s the steel industry adopted Argon Oxygen Depletion, AOD, furnaces for making steel for critical applications. This resulted in a dramatic reduction in the sulfur content in the steel. The traditional way of examining steel forgings for signs of overheat is by etching and polishing a sample to bring out iron sulfide contamination at the grain boundaries. This used to occur in the days of high sulfur steels and caused a characteristic “burning” of the steel, which was quite obvious on a micrograph.

Unfortunately, when forging overheat occurred, the ASM handbooks that the failure analysts referred to in order to detect forging overheat still printed the photos of the old high sulfur steel but did not explain the reasons that the photograph looked the way it did. The Lycoming and interstate metallurgists discounted forging overheat initially because the micrograph did not match the micrograph in the ASM handbook for forging overheat because the photo was taken of a high sulfur steel.

If the steel had reached temperatures even higher, there is a metalographic method of determining what is known as “incipient melting.” Samples of the failed crankshafts were examined to determine if incipient melting had

[4] American Society for Metals, Metals Handbook, 1939 Edition., American Society of Metals

occurred and the results were negative. Since these mechanisms do not rely on the presence of sulfur, it is improbable that the forging temperatures got high enough to cause incipient melting.

e. At what point in the manufacturing process did the honeycomb and microcracks form?

There are several things that indicate that the problem probably occurred at Interstate Forging. There are three points in the manufacture of the crankshaft where high temperature forging occurred, when it was forged from ingot to bloom at Republic Steel, when it was converted from bloom to billet at one of the rolling mills, and when the shaft was forged at Interstate.

1. In order for the honeycomb feature to have formed, the best data indicates that the temperature had to have been above about 2550 degrees F. During evaluation visits to republic steel, what records that were available were reviewed. It was apparent that republic had control of the furnaces and no temperatures were recorded that approached 2550 deg F. Lycoming Process specification LPS 483 specifies the forging temperature shall be between 2150 and 2350 deg F. According to the Aerospace Structural Metals Handbook, 4340 melts at 2740 deg F. Interstate did not record the temperature of the oven used, as required in the Lycoming specification, and the Lycoming audit indicated that the temperatures in the oven were probably significantly over the specification maximum. According to the report of the Lycoming evaluation in December of 2001 the temperature uniformity surveys had not been done. When requests were made during the FAA evaluation of interstate, Interstate stated that they did not have any records on the preheat furnace because it wasn't equipped with recording equipments. When the FAA team asked about uniformity surveys they were also told that no surveys existed.
2. The size of the honeycomb feature helps to tell us that it is much more likely that it was created at Interstate. In the production of steel, the prior austenite grains in the material get smaller and smaller through the production process at each step where forging at temperatures above the austenitizing temperatures is performed (some grain coarsening can occur if the temperatures are held above the austenitizing temperature for extended periods of time) We believe that the honeycomb feature is the result of a separation at the grain boundary during forging. As the grains get smaller and smaller, so do the boundaries. If the overheating had taken place at Republic, or it's rolling mills, the size of the grains would be larger, so the honeycomb feature would also be larger. The

size appears to be roughly equivalent to the size that grains are when the steel arrives at Interstate (see Figure 7-18). See Figure 7-19 for the statistical distributions of the grain sizes seen and the resulting microcrack size. Note that the distribution of prior austenite grain size prior to forging does not match the distribution of the observed microcracks by nearly a factor of 10.

3. Both Lycoming and Interstate's contracted lab looked for evidence of the honeycomb feature in the forging feed stock (4.5 x 4.5 inch billet) that was left over from several of the production runs that exhibited the honeycomb feature in the finished crankshaft. Neither lab found the honeycomb feature in the raw billet metallurgical labs

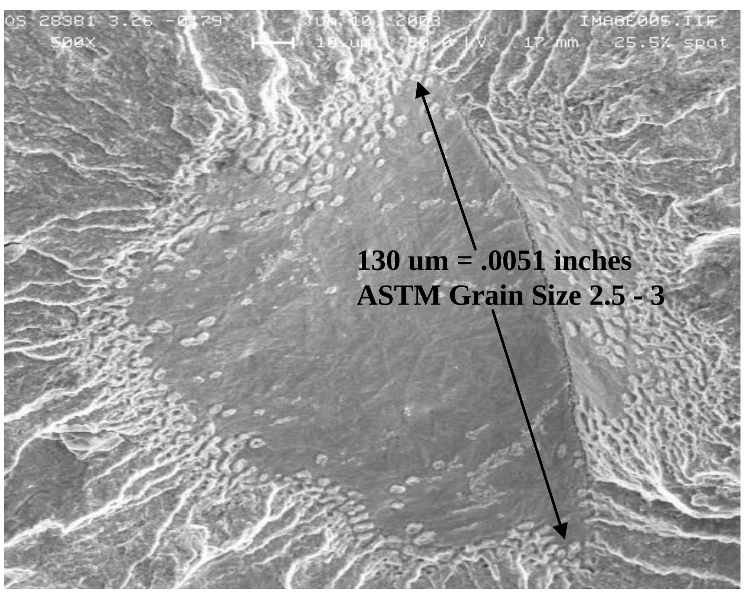


Figure 7-18 Grain size and microcrack from Barsom Fatigue test Specimen

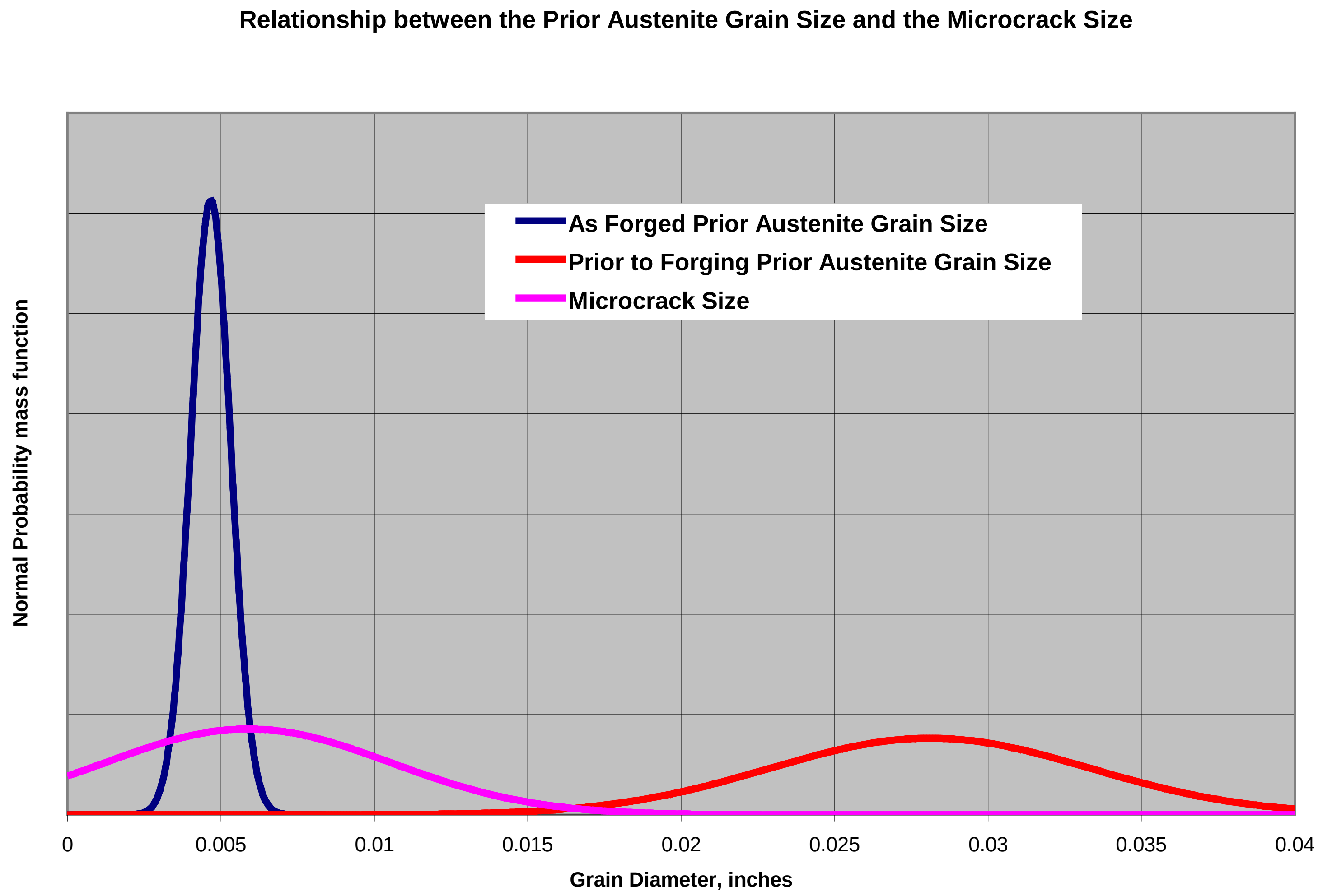


Figure 7-19. Distributions of microcrack size as they relate to the prior austenite grain size that exists after heat treatment. Data from Hinton Study of Honeycomb feature formation.

f. FAA Independent Investigation Overview

The tasks that the FAA independent investigation selected were:

- Verify alloy and heat treat to make sure that the base material met the specification limits and to find the trace element concentrations, particularly vanadium.

- Verify hardness profile due to nitriding by conducting microhardness traverses of the nitride layer in the critical zone.

- Examine samples of failed crankshaft to look for other metallurgical anomalies and to examine the steel for the honeycomb feature.

- Perform back to back fatigue testing and Charpy testing of samples removed from Wymann Gordon Shaft and from Interstate Forging.

1. General:

Specimens were examined from two complete crankshafts as well as sections from 3 crankshafts that failed in service. The crankshaft referred to as the Krupp shaft was a press forged crankshaft that was removed from service at overhaul. It had multiple overhaul cycles on it and had performed well. It was serial number V15703. The FAA investigation determined from the Charpy samples that this shaft did not have the honeycomb feature.

The interstate shafts examined were removed from service by Lycoming service bulletin 550 and were examined at Seal Beach by FAA metallurgists and were positive for the honeycomb feature. They were serial numbers V537916975, 537912910, and 537916018. The FAA investigation confirmed that, at least the shaft examined, did indeed have the honeycomb feature.

2. Verification of alloy and heat treat

The alloy composition and hardness met specification levels. The drawing requirements for core hardness are Rockwell C scale 32-39 per 13F27708 Revision J. Hardness was checked on 18 samples, 6 readings from actual failed crankshafts, 3 baseline readings from the Krupp shaft that did not fail and 9 readings from interstate suspect shafts that did not fail. All the reading were within specification limits, and there was no significant difference between the readings from the shafts that failed, the baseline shafts, or the suspect lot interstate shafts. The measured hardness from the failed crankshafts were ranged from a low of 32.9 to 35.8, well within drawing tolerance.

Semi quantitative chemical analysis of the Krupp shaft, the Interstate shaft and the samples from the Chemical analysis was within specification limits. The Krupp sample did not show any vanadium to the limits of detectability in the EDS analysis. During many examinations of the honeycomb feature in the Interstate shafts, vanadium was not detected.

2. Verification of hardness profile due to nitriding

Figure 7-20 below was taken during the FAA independent investigation at Seal Beach. This journal was taken from a failed crankshaft. The dark area shows the difference in the etch response in the nitrided area. This shows the depth of penetration of the nitride layer in the critical area. Note the absence of “white layer.” This is a detrimental layer on the surface that has been well documented to cause problems in fatigue.

The depth of penetration and the phase transformations observed in the nitride layer are normal for a nitride process that is under control. Optically measured, the depth of penetration is about .031 inches in this case, which puts the transition between the case and core at the same location as the crack origin. The hardness profile varies somewhat in the cheek area as opposed to the center of the radius as shown in Figure 7-21. The cheek area was very slightly harder and had slightly greater depth of penetration than seen in the center of the radius. This is to be normal due to the nature of the nitrogen diffusion processes responsible for the nitriding and is compliant to the Lycoming process specifications.

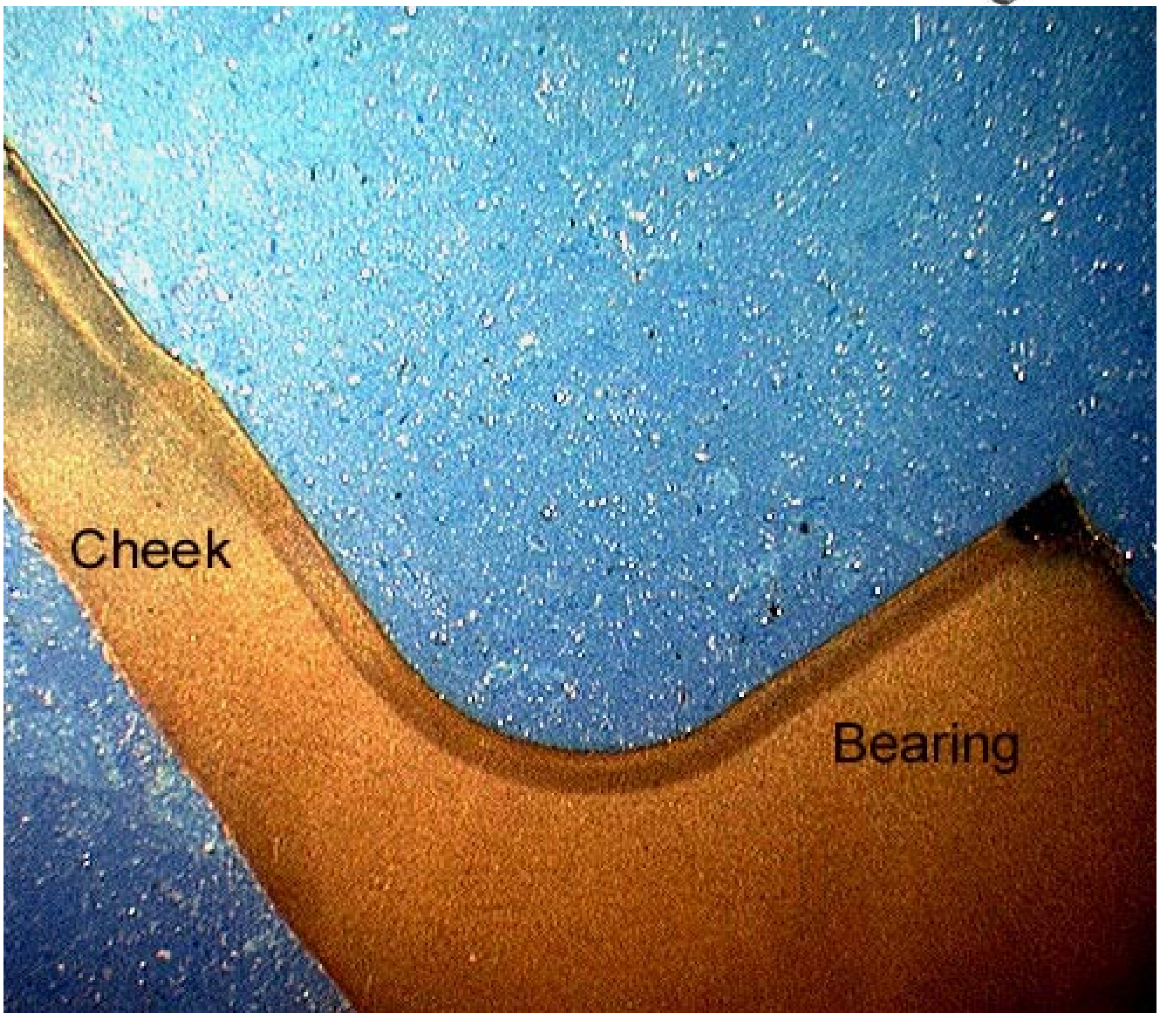


Figure 7-20 Metallographic section of the critical journal showing the nitride layer.

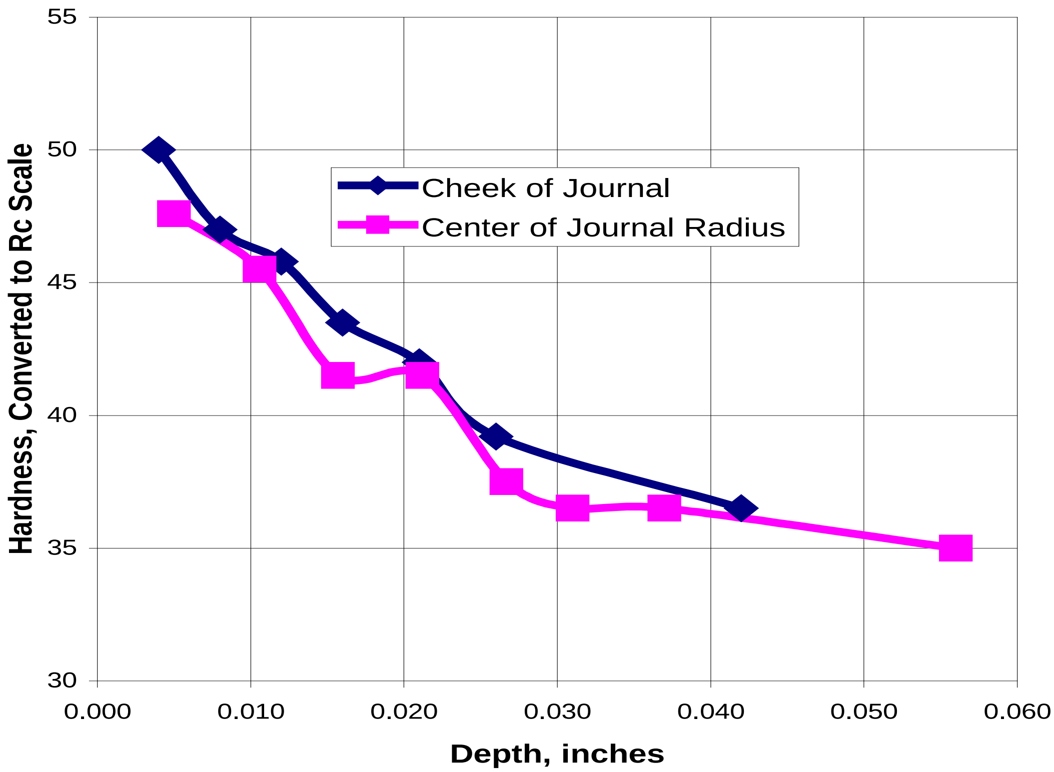


Figure 7-21 Hardness Profile with Depth in the Critical Journal area of the Crankshaft

3. Examination of Crankshaft Specimens

Contrary to what some have said in the past regarding vacuum arc remelting, it does not remove all inclusions from the steel. It didn't when the previous vendor, Krupp, forged the crankshaft, and it didn't when Interstate forged essentially the same steel. The introduction of vacuum remelting was a process improvement that was intended to reduce the size and numbers of inclusions and has successfully done that according to data in the Aerospace Structural Metals Handbook.

The FAA investigated inclusions in Vacuum Arc remelted steel from both Krupp shafts Interstate shafts (see Figure 7-22). The intent behind this investigation was not to imply that these inclusions had anything to do with the failures of the crankshafts in this case, but to document it for the future. Houston Metallurgical, FAA at Seal Beach, Barsom, and Lycoming labs, found numerous other examples of small nonmetallic inclusions. These are normal in VAR melted 4340 and are acceptable per the requirements of AMS 6414.

In the event that establishing controls over the forging processes solves this problem, the next larger defect that is present, even in vacuum arc remelted material, will be these inclusions. If future versions of these engines drive the stresses up, these inclusions will become critical defects as described in the fracture mechanics section.

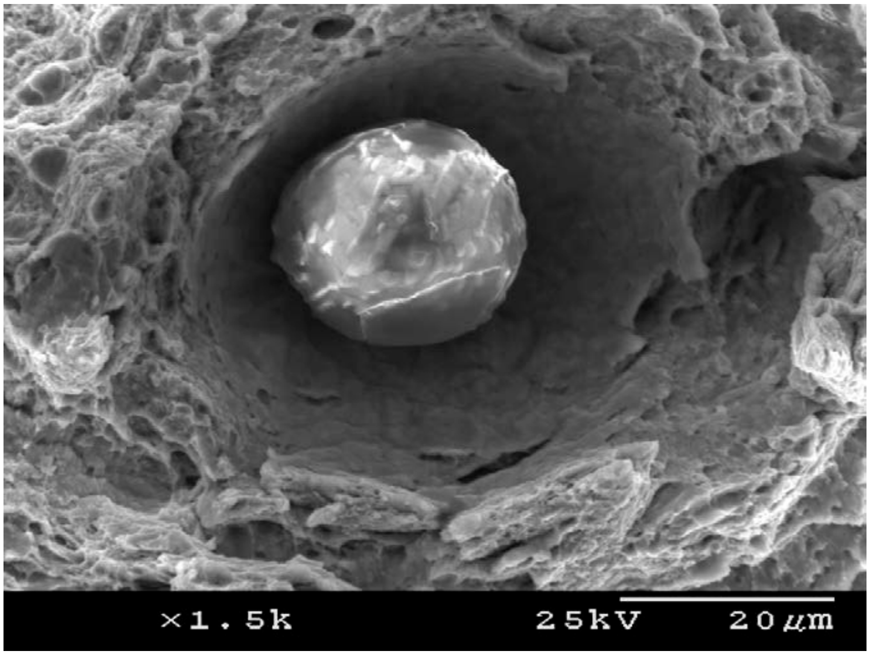


Figure 7-22 Photo taken from Krupp shaft showing small non-metallic inclusion.

4. Back-to-back fatigue and Charpy testing of Crankshaft Specimens

The results of the fatigue testing revealed that the specimens removed from the crossover cheek areas of the Interstate crankshaft failed under 10 million cycles at 125 ksi, and the specimens removed from under the front main bearing didn't. In addition, none of the samples removed from the Krupp shaft failed during testing indicating an infinite fatigue life at that stress level (see Section c).

g. How reliable is the Charpy test for detecting the presence of the honeycomb feature and the microcracks?

Both Lycoming and TCM have used the Charpy test with some success to screen for the "honeycomb feature." The feature, due to its small size, is usually impossible to detect by optical microscopy. A Scanning Electron Microscope (SEM) must be used. The honeycomb feature is present only in few locations that are far between. Therefore, it is reasonable to anticipate that SEM inspection may not "catch" all affected specimens. This is further compounded by the fact that the Charpy specimen, due its small size, may not represent the crankshaft.

The probability of a "false-negative" is the Charpy test is probably fairly high. Validation of this view comes from the most recent TCM failure, which took place in low V steel that was SEM screened. The Charpy test only shows one fracture plane, so if that plane does not contain the Honeycomb feature, it will not be detected. A typical Charpy test set-up is shown in Figure 7-23.

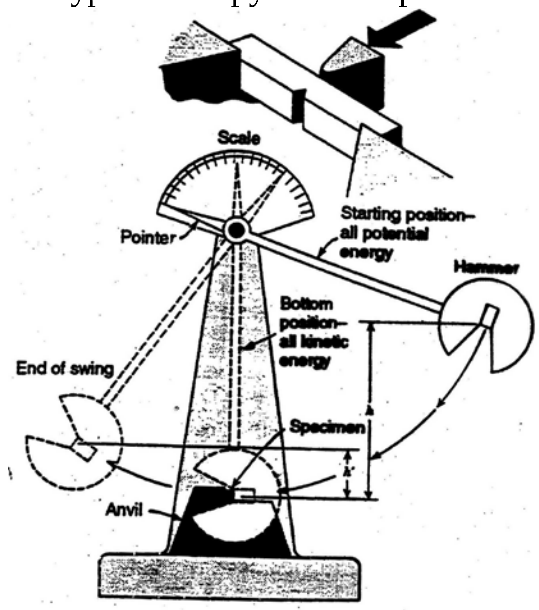


Figure 11. Standard impact-testing apparatus. (Source: From H.W. Hayden, William G. Moffatt and John Wulff, Mechanical Behavior, Vol. 3 of The Structure and Properties of Materials, John Wiley and Sons, New York, 1965)

Figure 7-23, Diagram of the Charpy Impact Test

h. Is the addition of Vanadium to the steel related to honeycomb and microcrack formation?

The SCRT Team does not believe that the addition of Vanadium and establishing control over the vanadium content in early 1999 was the cause of the failures. It may have been one contributing factor and there are significant issues relating the certification of the new alloy that was created when that was done. The team believes that it could have been a small contributing factor due to the relatively small reduction in the temperature at which delta ferrite forms in the presence of vanadium. Lycoming did virtually no alloy characterization or allowable generation work when vanadium was added. Lycoming considered the addition of Vanadium and the associated changes in the heat treatment processes necessary to be minor changes to type design. The SCRT disagrees on this point.

The Vanadium addition was done to eliminate distortion problems that were resulting in unacceptable balancing conditions. By adding Vanadium, Lycoming was able to increase the tempering temperatures, thereby getting a better stress relief of forging residual stresses. When this was done, the balancing problems virtually disappeared.

Metallurgically speaking, Vanadium is a very active alloying element in steel. It has been used in many alloys for a variety of reasons. It has been well established in a variety of sources that Vanadium in the concentrations seen has a definitive effect on the heat treat response and the mechanical properties of steel.

The material specification used by Lycoming for steel is AMS 6414 which does not control the vanadium content, except that it does limit any single element to no greater than .15%. In 1999 Lycoming added Vanadium to the drawing requirements for the crankshaft at a concentration of .07 to .11 % by weight. Figure 7-25 shows the historic concentrations of Vanadium and the resulting concentrations after the addition of the requirement on the crankshaft drawing as a function of time. The upper and lower specification limits begin on the date that the revision was released to the crankshaft drawing.

Base on publicly available data, Vanadium has the following effects on the metallurgy of steel in general[5,6,7,8,9,10,11,12,13,14,15]. Little data is available on the

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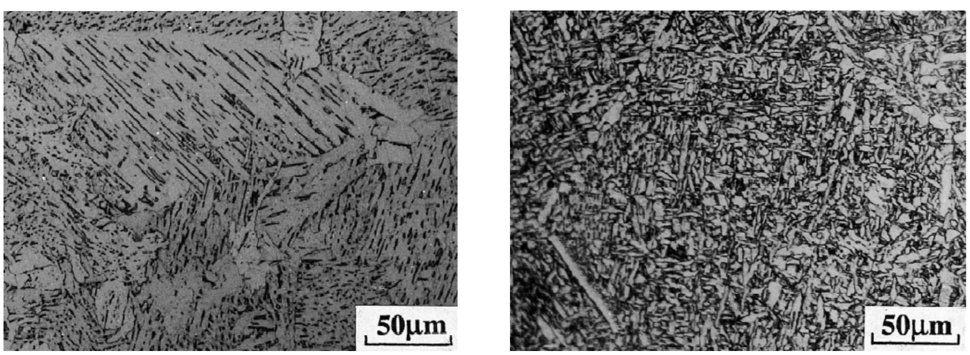
[5] Wegst, C.W. Stahlschlussel Herausgabe und Vertrieb, 1995
[6] Bain, , E.C., Paxton, H. W., Alloying elements in Steel, American Society for Metals, 1966
[7] Woodhead, J.H., The Physical Metallurgy of Vanadium Steels, 1983
[8] Kesri, R., Durand-Charre, M., Metallurgical Structure and Phase Diagram of Fe-C-V System: Comparison with other systems forming MC Carbides, Materials Science and Technology, August 1988, Vol. 4
[9] The Effect of Vanadium and Niobium on the Properties and Microstructure of the intercritically Reheated Coarse Grained Heat Affected Zone in Low Carbon Microalloyed Steels.,
[10] Jafre, R., Effects of the Elements on Steel Properties, a Summary., Unpublished
[11] He. K., Edmonds, D.V., Formation of acicular Ferrite and Influence of Vanadium Alloying., Materials Science and Technology, March 2002 Vol 18.
[12] Li. P., Todd., F.A. Application of a New Model to the interphase Precipitation Reaction in Vanadium Steels., Metallurgical Transactions A, Vol. 19A, September 1988
[13] Horton, S. A., C hild, H. C., Relationship between Structure and Fracture behavior in 6W-5Mo-2V Type High-Speed Steel, Metals Technology, July 1983

effects on Vanadium in vacuum arc re-melted 4340 steel because Lycoming has done no qualification or alloy development work. The papers and books cited reflect overall trends, but the development of fatigue data and allowable data for a specific alloy is typically left to the companies developing the material. Summarizing all the effects of an alloying element for the audience of the report is quite challenging and such, at times contradictory information is available. We believe that the following points are generally agreed to with respect to Vanadium addition in Steels.

1. Vanadium is a strong carbide and nitride forming element. Relatively low concentrations will preferentially form carbides over carbides formed with other alloying elements. This provides increased wear resistance, increased high temperature strength.
2. Vanadium acts to prevent the austenite grains from coarsening during elevated temperature exposure, resulting in improved fatigue strength and improved static strength. Figure 7-24, taken from He and Edmonds, shows the grain refinement in steel containing .23% vanadium compared with one without. Note the finer structure in the picture taken of the steel with .23% Vanadium.



Vanadium Free Steel

Steel with .023% Vanadium

Figure 7-24, Grain refinement due to the addition of Vanadium.

3. Vanadium acts to increase the temper resistance of steel. This means that higher tempering temperatures are required to attain the same hardness after temper. In the case of the Lycoming heat treat specifications, when the Vanadium was added the tempering

[14] Hara, H., Kobayashi, M., The use of Hot Forged Microalloyed Steel in Automobile Components., Institute of Metals Vanadium Award Paper, 1987
[15] Langenborge, R., Stanislaw, Z., A Model for interphase precipitation of V-Microalloyed Structural Steels., Metallurgical and Materials Transactions A, Vol 31A, Month 2000-1

temperature had to be increased by about 100 degrees F in order to achieve the same hardness.

4. Vanadium acts as an Austenite destabilizer. This means that the addition of vanadium will lower the temperature when the austenite grains will melt or transform to delta ferrite. (Whether delta ferrite forms or the grains begin to melt is the subject a debate) Since melting occurs at the grain boundaries first, this will tend to cause problems at the grain boundaries at lower temperatures than would occur without vanadium. Estimating the magnitude of this effect is made difficult because Lycoming didn’t generate any of the baseline data when the addition of Vanadium was made. An estimate based on the data in Bain’s book referenced below is somewhere in that range of a 30 degree F reduction in the melting temperature of Austenite due to the addition of .1% V. This would in essence reduce safety margin at the top of the forging temperature before bad things happen.

There are other relevant effects that have been found by some metallurgists that are discussed in some sources but have not necessarily been independently verified. Some of the relevant issues are:

1. Some metallurgists have observed the segregation of Vanadium to Austenite grain boundaries at elevated temperature. This view led some early investigators to believe that the addition of the Vanadium was the causal factor in forming the honeycomb feature.

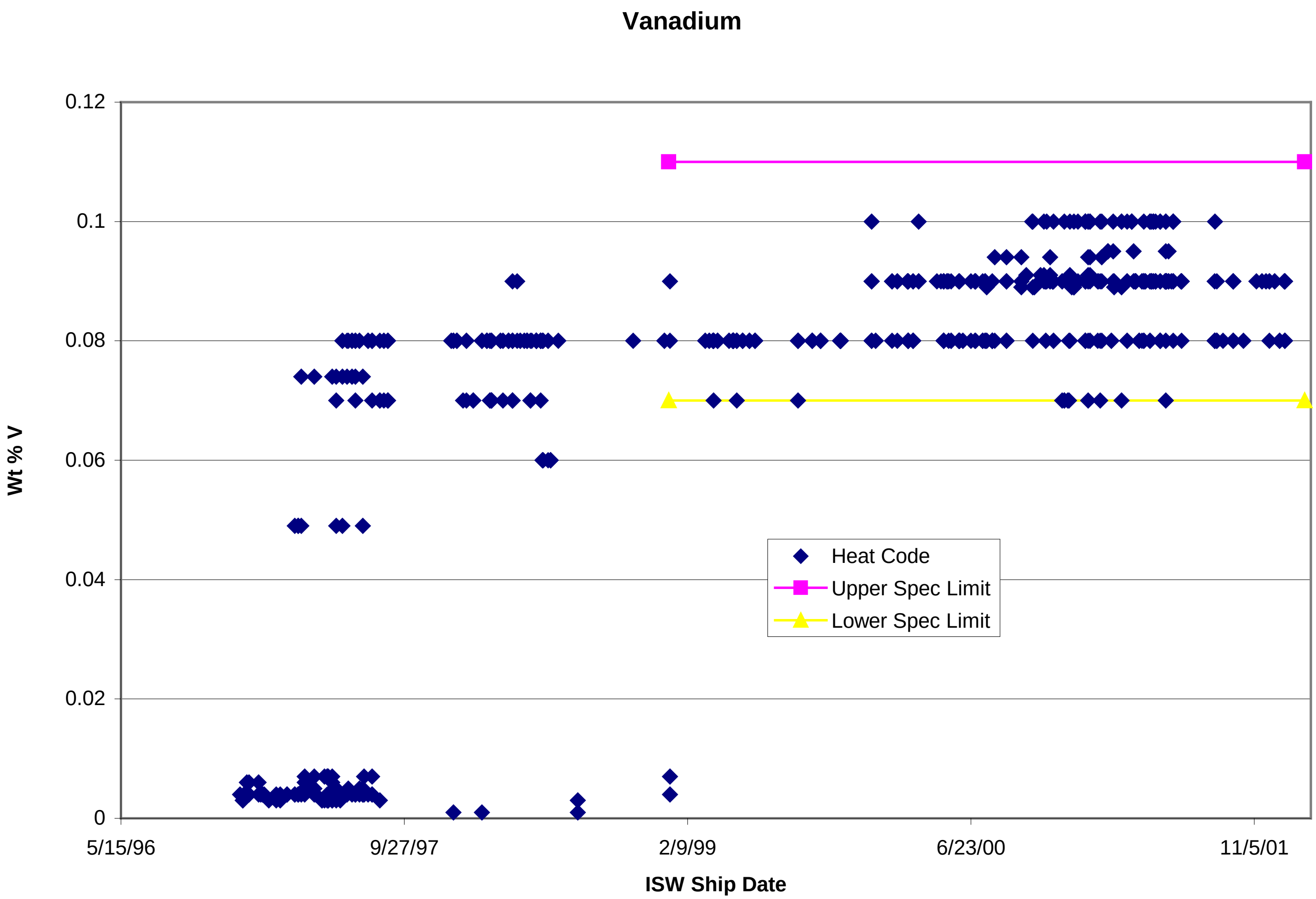


Figure 7-25 The History of Vanadium in production at Interstate Forging

i. Definitions

Austenite:
Austenite is a face center cubic form of iron that is stable at elevated temperatures (red hot). In this case, during the forging of the crankshaft when the dies close the steel exists as austenite. If the crankshaft is allowed to cool slowly, such as after forging, it will transform into pearlite, another crystal structure found in steel. If it cools rapidly, such as when the crankshaft forging is quenched after heat treat, it will transform into Martensite.

Martensite:
Martensite is a body centered tetragonal crystal structure that exists in quenched steel. Before tempering it is extremely hard and brittle. Tempering the Martensite results in softer steel that is less sensitive to minor nicks, scratches, and other defects like the honeycomb feature. Tempered Martensite is the normal phase for bulk material in a completed crankshaft.

Prior Austenite Grain Size:
The prior Austenite grain size refers to the average diameter of the grains in the steel when it was still austenite, in this case before the forging dies closed. When the steel transforms from Austenite to Martensite as the steel is quenched, the Martensite crystals form within the Austenite grains (see Figure 7-26). This leaves the old austenite grain boundaries in place. This is important in this case because there have been attempts to compare the size of the honeycomb feature, and the resultant microcrack, to the size of the prior austenite grain boundaries.

In general it appears, with the limited data that exists, that the size of the honeycomb feature is roughly consistent with the facet size of the prior austenite grains, as they existed during forging[16]. Each time the steel is heated above the austinitizing temperature, the austenite reforms. Each forging operation refines the austenite, causing the grain to become smaller.

(They are called “prior” Austenite grains because when the material cools to room temperature, the steel transforms to either Pearlite or Martensite.) We believe that the microcracks form along these prior austenite grain boundaries.

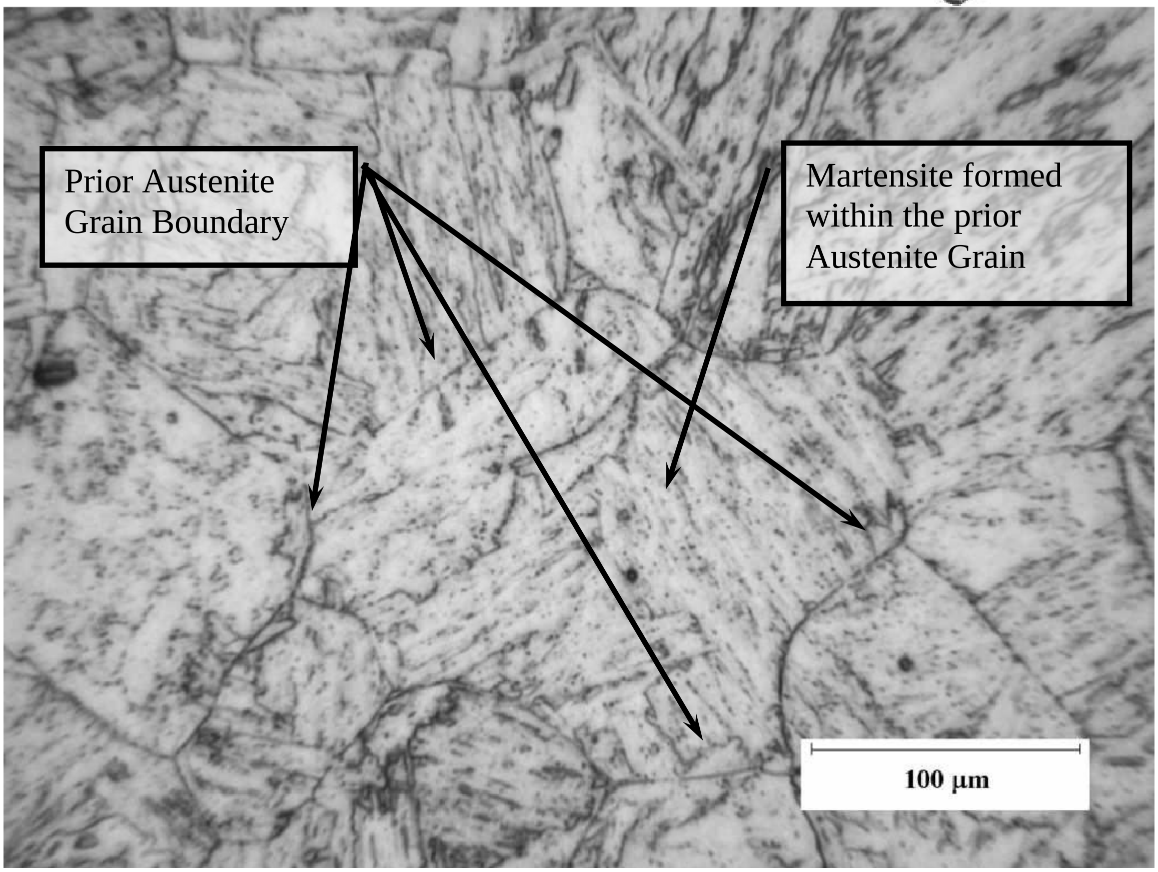


Figure 7-26, Prior Austenite Grain boundaries with Martensite within the grains

Decarburization:

Decarburization occurs when steel is exposed to elevated temperatures in normal air. Some of the carbon in the steel on the surface combines with oxygen in the air and forms carbon monoxide or carbon dioxide, resulting is a weak low carbon layer on the surface of the part. To avoid this, the Lycoming process specification requires the use of a carbon rich or “endothermic” atmosphere in the heat treat furnace. Specialty heat treat, who heat treated the failed crankshafts, did not have the equipment to provide an endothermic gas environment, thereby violating the specification. This probably did not contribute to the failures experienced because the surface decarburation layer was removed during machining after heat treatment as verified by spectrographic measurements of the carbon content of the steel at the locations where the cracks formed.

Nitriding:
Nitriding is a surface hardening process used to harden the crankshaft bearing journals. This is done by exposing the finished machined shaft to a cracked ammonia atmosphere at elevate temperature for about 24 hours. Exposure to nitrogen hardens the surface layer of the shaft by forming nitrogen carbide particles and introduces a residual compressive layer at the surface of about 150 ksi due to the expansion of the material at the surface. This residual compressive stress is balanced by a residual tension stress in the remaining subsurface area. This residual tension stress peaks at about .030 inches below the surface, which is where the origin of the fatigue crack has been in the failed crankshafts. Figure 7-27, taken form Cessna Aircraft Corporation measurements of a failed crankshaft, shows how the hardness of the steel varies with depth and Figure 7-28 shows an actual nitride layer.

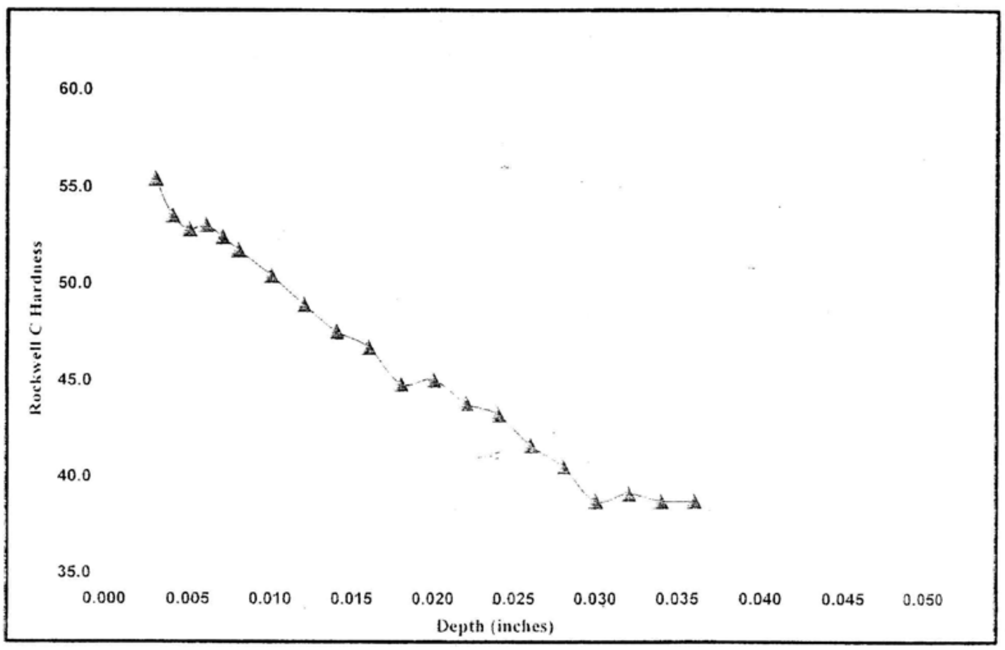


Figure 7-27, Variation of hardness with depth from Cessna Failure analysis. Normal nitride layer that met the specification requirements

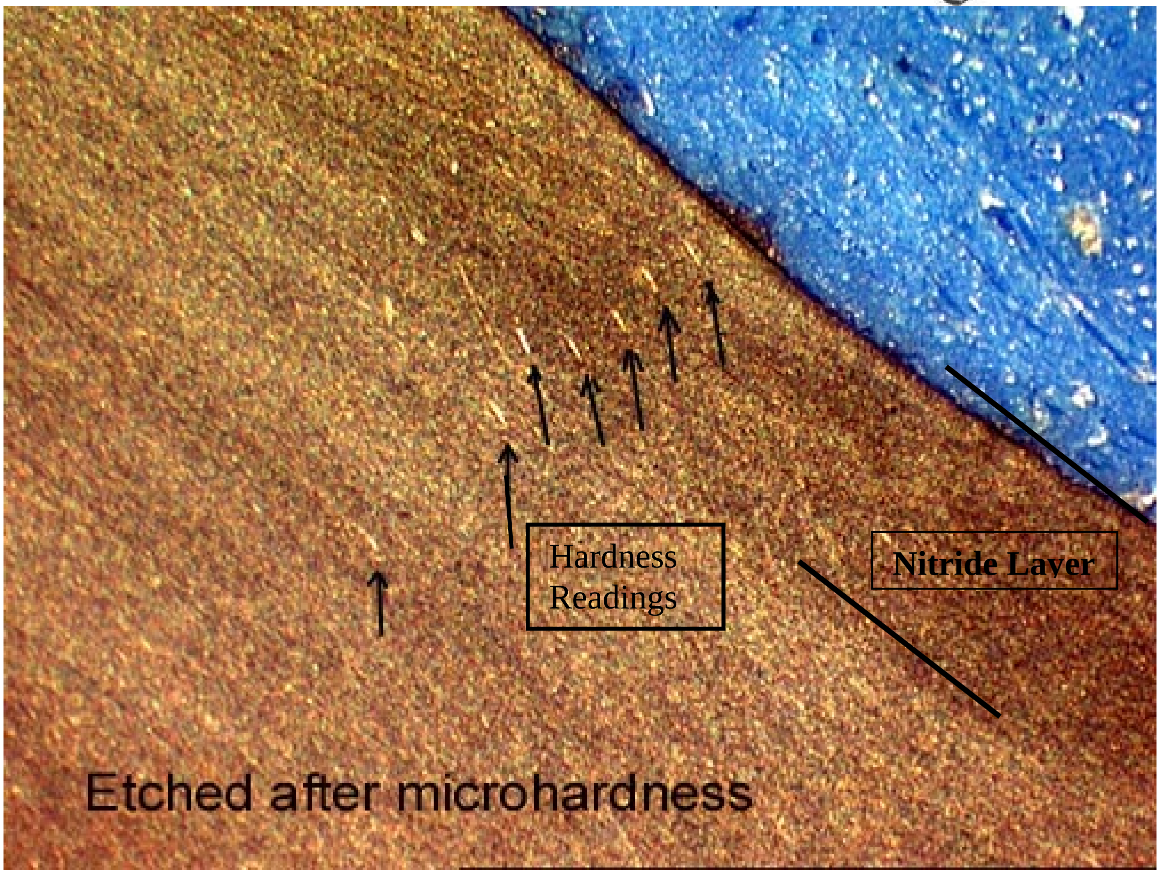


Figure 7-28 Locations for hardness readings showing the nitride layer on the number 5 Crankshaft piston pin journal. Photo taken during FAA investigation at Seal Beach Labs. (Results very similar to Cessna Study)

Hammer Forging:

Hammer forging is a process where red-hot steel is struck with a successive series of dies to shape it into the desired configuration. Interstate used a two-step hammer forging process, whereas the previous vendor, Wymann Gordon, used a three-stage process using a slower die closure rate (press forging). Hammer forging differs from press forging in that the dies close at a very rapid rate, requiring the steel to undergo very high strain rates to flow into the die cavities. The die forging process is suspected of introducing high residual stresses during the initial production run at interstate, resulting in distortion of the crankshafts during machining.

Press Forging: Press forging differs from hamper forging in that the forging dies are closed more slowly. In addition, the processes used by Wymann

Gordon for press forging contained additional process control steps that were not present in the interstate forging processes. Press forging is done slowly enough that the metal is allowed to recrystalize as it flows into the cavities in the forging die. The end result is that the press-forged crankshafts appear to have a finer grain structure. Finer grain is typically associated with an increase in strength and a longer fatigue life. Hall and Petch related this mathematically in the Hall-Petch relationship for describing the Strengthening due to grain refinement[17]. $\sigma_0 = \sigma_i + kD^{-1/2}$

Vacuum Arc Remelting:
Vacuum Arc Remelting, or VAR is a processes used in making the steel to remove harmful inclusions. It was introduced as an additional processing step in the late 1970's to improve the fatigue life of crankshafts and other steel forged critical rotation components. The process works by taking a cast ingot of steel, and remelting it using an electric arc in a vacuum. Volatile impurities are pulled away with the vacuum and other impurities are dissolved in the steel or float to the surface and are cropped off before the ingot is used. This process has successfully allowed an increase in the operational stresses due to power increases without the increase in fatigue failures that would otherwise have resulted. It is important to note that while VAR melting does reduce the size and number of inclusions remaining in the steel, a single VAR remelt does not eliminate them entirely. The VAR furnace is shown in figure 7-29.

[17] Dieter, G. Mechanical Metallurgy, third edition, McGraw Hill, 1986

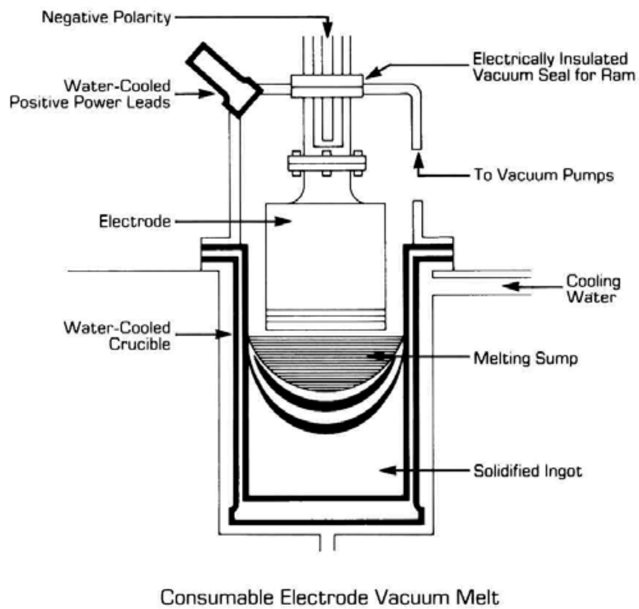


Figure 7-29, Vacuum Remelting, courtesy of Republic Steel

LESSONS LEARNED

a. Honeycomb Feature: The honeycomb feature was caused by overheating the billet at Interstate prior to forging.
b. Charpy Test: The Charpy test is a reliable method of verifying that the temperature of the forging was not exceeded. It is imperative that the samples be removed from forgings in areas where the material was in tension during the forging process. The present location where Charpy specimens are removed from the forging prolong appears to be acceptable based on correlations with specimens removed from the critical area.
c. Material Inclusions: Inclusions exist in the material that are consistent with quality levels required in VAR melted steel per AMS 6414.
d. Vanadium: Vanadium addition to the steel was successful in eliminating distortion, but may have reduced the margin between the maximum allowable forging temperature and the temperature at which the honeycomb feature would form.

RECOMMENDATIONS

a. <u>Charpy Test:</u> The Charpy test, or other equivalent means, should be an integral element of statistical process control procedures for steel forging process. This should be done for all critical fatigue loaded steel parts in reciprocating engines.
b. <u>Process Control:</u> Process control is essential at the vendor to make sure that the forging temperatures are not exceeded.
c. <u>New Alloys:</u> The specification of a new alloy in a critical part design should be classified as a major design change.

Appendix 1
Reference Documents

Chapter 4: Certification Process Evaluation Reference Documents

Engine Type Certification:

1. FAA Form 312 – Application for Type and Production Certificate Lycoming Model TIO-540-A1A
2. FAA Form 317 – Statement of Conformity
3. Specification 2300A - Preliminary Detail Specification Model TIO-540-A1A
4. Performance Test per CAR 13.152, 15.153 – Report No. 2643
5. Torsional Test Survey of TIO-540-A1A Engine with Hartzell Model HC-E2YK-2/C8465 Propeller per CAR 13.151 – Report 2668
6. Torsional Test Survey of TIO-540-A1A Engine S/N 528-X with Hartzell HC-E2YK-2B/C8475 & HC-HC-E2YK-2B/C8475-4 Propellers per CAR 13.151 – Report 2753
7. 150-Hour Endurance Test Schedule of Lycoming TIO-540-A1A Engine, S/N 548-X per CAR 13.154, 13.155, 13.157 – Report 2731
8. 150-Hour Endurance Test Schedule of Lycoming TIO-540-A1A Engine, S/N 589-X at 500 degree F, Cylinder Head Temperature and of Alternate Parts per CAR 13.154, 13.155, 13.157– Report 2776
9. ENPL (Engine Parts List) 2297 for TIO-540-A1A

Major/Minor Design Changes:

1. ECO 13464, dated 1/10/66, Forging from 75291 to 76761
2. ECO 16753, dated 8/4/71, Increase bearing clearance
3. ECO 20147, dated 10/19/77, Change hardness callout
4. ECO 20235, dated 12/22/77, MRB/Cold Straightening
5. ECO 20596, dated 8/25/78, Vacuum melt Crankshafts
   a. Lycoming report dated Jan. 22, 1974, “Test of 4340 (AMS 6415) Crankshaft Steel”.
   b. Lycoming report dated December 9, 1971, “Fatigue Information Type 4340 Steel Tested in the Longitudinal and Transverse Direction”
6. ECO 20716, dated 11/29/78, Vacuum Melt Steel
7. ECO 22736, dated 11/17/86, Drop forge to Press forge

8. ECO 22791, dated 4/30/87, Facilitate Manufacturing
9. ECO 22879, dated 3/4/88, Clarify Part Requirement
10. ECO 23773, dated 1/18/91, Modify Print
11. ECO 24207, dated 11/23/92, Standardize O-540 crankshafts
12. ECO 24309, dated 3/23/93, Facilitate Manufacturing
13. ECO 25139, dated 7/29/97, Krup to Interstate
    a. Materials Laboratory Report, Part Number F13F17707, AMS 6414 material, dated 4/10/97
    b. Lycoming First Article Conformance Report, Part Number 17707, Revision Textron F13F17707 Rev G
14. ECO 25352, dated 11/16/98, Increased Vanadium
15. ECO 25499, dated 12/14/99 Revise Sheet 2 of Dwg. Showing Interstate Forging configuration
16. ECO 25450-A, dated 1/20/01, Update Drawing
17. ECO 25789, dated 10/23/01, Facilitate Engine Build
18. ECO 25769-A, dated 10/23/01, Hammer Forged to Press Forged
19. ECO 25803, dated 12/13/01, Return to Std Material Designation (Vanadium)
20. ECO 25850, dated 3/13/02, Facilitate Manufacturing
21. ECO 25850-B, dated 5/16/02, Facilitate Manufacturing
22. ECO Not Issued, dated 8/18/82, Narrow Pin Crankshaft
    a. TIO-540-U2A engine certification reports:
        - 150 hours FAA witnessed model test Report # 3589
        - Crankshaft Torsional Survey Report # 3585
        - Type Test Parts List (ENPL)
        - Detonation Survey and Performance Report # 3588
        - Engine Spec. # 2573 A and 2574-A
        - Pre-Test conformity Inspection
    b. Lycoming Engineering Report No. 3604, "Crankshaft Stress Survey for TIO-540-J2BD and TIO-540-U2A Engines", dated 18 August 1982.
    c. Lycoming Engineering Report No. 2825, "IGSO-540 Crankshaft Increased Strength Program", dated June 30, 1966
    d. Lycoming Engineering Report No. 2590, "Preliminary Stress Analysis of the Power Section of the IGSO-540 (400 HP) Engine", dated February 7, 1964

Manufacturing Process Changes:

1. LPS 468-U, dated 3/13/02, Heat Treatment of Steel

    a. ECO 17795 dated 3/21/73 updated revision levels of specification cover sheet.

    b. ECO 18774-dated 1/2/75 for AMS 6440, added temperature and time requirement after quenching.

    c. ECO 18853 dated 3/11/75 added sheets 5, 6, 7 for carbon restoration process.

    d. ECO 20596 dated 8/25/78 added AMS 6414, changes Anneal, Harden, Stress Relieving.

    e. ECO 20864 dated 4/2/79 clarification of decarburization and carburization.

    f. ECO 21457-A dated 6/4/81 added heat cycle for AMS 5120/5122.

    g. ECO 22613 dated 2/24/86 complete re-write, removed all instruction sheets, referenced applicable Military Standards for AMS materials. This change reduced the LPS from 40 sheets to 11 sheets.

    h. ECO 23255 dated 6/1/89 complete re-write.

    i. ECO 24627 dated 1/3/95 changed furnace temperature uniformity requirements for nitriding on sheet 2, changed method of hardness testing on sheet 7.

    j. ECO 24841 dated 2/23/96 changed furnace temperature uniformity requirements for hardening, carburizing, and tempering on sheet 2 to meet industry standards.

    k. ECO 25509-C dated 3/29/00 clarifications and updated to meet industry standards and current AMS specifications.

    l. ECO 25850-A dated 3/11/02 process changes to facilitate supplier (Interstate Forge) manufacturing based on FAA audit findings.

m. ECO 25953 dated 1/17/03 updated process, removed Military Specification MIL-S-851 “Steel Grit, Cut Wire, Iron Grit, and Shot Blast Cleaning and Peening”.

2. LPS 483-M, dated 12-6-02, Steel Forgings

3. LPS 555-G, dated 2-24-03, Crankshaft Balancing Procedure

   a. ECO 23233 dated 5/17/89 added new forging part numbers and changed LW-17707 to 13F17707.

   b. ECO 23757 dated 1/22/91 added new forging outlines.

   c. ECO 23959 dated 8/20/91 changed forging part numbers.

   d. ECO 25452 dated 7/26/99 changed RPM requirements, removed calibration weight requirement and revised 1.41 max to “MAX” (to centerline).

   e. ECO 25504 dated 12/16/99 removed metal stamping requirement.

   f. ECO 25846 dated 3/7/02 added 4cylinder secondary stock removal cheeks #3 and cheeks #4.

   g. ECO 25959 dated 1/27/03 revised/added new forging part numbers.

4. LPS 496-E, dated 8-4-99, Stress Relief and Straightening of crankshafts

   a. ECO 18863 dated 3/14/75 changed “Routing” to “Instruction Sheet”.

   b. ECO 20830 dated 3/15/79 added the “Straightening of Nitrided Crankshafts” requirements.

   c. ECO 21294 dated 9/4/80 added “Room Temp. Stress Relief (Alternate Method)”.

   d. ECO 25436 dated 6/16/99 reduced time at temperature from 25 hrs. min. to 10 hrs. min.

5. LPS 366-G, dated 4-10-00, Nit riding of Aircraft Parts

Chapter 5. Installations/Operations Evaluation Reference Documents

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2. Piper Report FT-170, Flight Test Certification PA-46-350P, dated August 8, 1988 with Revisions through B dated June 18, 1990.
3. Piper Report VB-1710, Pilot's Operating Handbook and FAA Approved Airplane Flight Manual Malibu Mirage PA-46-350P S/N 4636196 and up, dated February 23, 1999 with revisions through November 8, 2002.
4. Textron Lycoming Report 3663, Development Detonation Survey and Performance of Textron Lycoming TIO-540-AE2A Engine, S/N L-1158-X, dated July 25, 1988. (Contained in Appendix A of Item 1)
5. Textron Lycoming Communication Report 972, In-Flight Evaluation of 5.3 Compressor Trim and Partial In-Flight Detonation Survey on the TIO-540-AE2A Engine, dated October 3, 1988.
6. Textron Lycoming Specification Number 2623-I, Detail Specification for Engine, Aircraft, Model TIO-540-AE2A, 350 Horsepower, Direct Drive, Turbocharged, dated March 2, 1998 (revisions through I).
7. Textron Lycoming Operator's Manual TIO-540-AE2A Aircraft Engine, Lycoming Part Number 60297-27, dated September 1988 with revisions through 2 dated March 1999.
8. Type Certificate Data Sheet E14EA Revision 16, Textron Lycoming TIO-540 Series Engines, dated February 12, 2001
9. Type Certificate Data Sheet A25SO Revision 10, New Piper Aircraft PA-46 Series Aircraft, dated January 2, 2002.
10. Airworthiness Directive AD 95-23-12, Manifold Pressure and Engine Speed Limitation Placard PA-46-350P.
11. Airworthiness Directive AD 99-15-04 R1, TIT System Cleaning, Calibration and Replacement PA-46-310P and PA-46-350P.
12. Service Difficulty Report Database for "Piper" "PA46-350P" through January 27, 2003.
13. Service Difficulty Report Database for "Cessna" "T206H" through September 2003.
14. Type Certificate Data Sheet A4CE Cessna 206 Series Revision 41, dated March 3, 2003.
15. Cessna Report T206H PH US 00 Pilots Operating Handbook and FAA Approved Airplane Flight Manual T206H dated November 9, 1998.

16. Cessna Report DMT206H-0 Flight Test Certification T206H dated June 10, 2002.
17. Cessna Report T206H-96-001 Drawing 1250983 Powerplant Installation Model T206H dated September 20, 2002.
18. Cessna Service Bulletin SB 02-71-02 Revision 1 dated December 23, 2003 Engine Crankshaft Core Sample Inspection.
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2. X-ray lab report, Lambda Research, Inc. report 400-11266, dated Sept. 5, 2003

Chapter 7. Metallurgical Working Group Reference Documents

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