Engine Titanium Consortium - Phase III

Project 1 – Nondestructive Evaluation (NDE) of Manufacturing Induced Anomalies

Project 2 – Thermal Acoustic Studies of Engine Disk Materials

Quarterly Report

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Project 1: Nondestructive Evaluation (NDE) of Manufacturing Induced Anomalies

Background

Propulsion systems are comprised of components that undergo a variety of manufacturing processes to arrive at the final engineered system. Catastrophic failures have resulted from shortcomings in manufacturing processes, both materials discontinuities and machining/handling anomalies. Significant efforts have been completed to address inspection for material discontinuities for rotor grade titanium and nickel alloys as part of the Engine Titanium Consortium (ETC) Phase I and II programs. Machining induced anomalies for both titanium and nickel alloys also present a threat to flight safety with incidents attributed to their occurrence in 1996 and 1999[1]. Anomalous machining damage (AMD) can result in "disturbed microstructure" which can have a detrimental effect on local properties and lead to crack generation. As an example, "alpha case" can result in titanium alloys when surface temperatures exceed recommended levels. Etchant processes are in place as a quality control check for alpha case and other anomalies in Ti and Ni. However, the need for assessment tools that could provide for corrective actions and damage quantification tools once the anomalous microstructure has been detected, have been identified.

Manufacturing induced anomalies in rotating components can limit engine life if not detected before the part is introduced into service. These anomalies may result from issues in the manufacturing process, and are usually detected immediately by the machine operator. However, not all anomalies are visually detectable. To address these manufacturing anomalies, it is necessary to use a combination of process controls, process monitoring, and inspection to minimize their occurrence and/or escape and to detect their presence. This program is focused on using nondestructive evaluation (NDE) of the component to detect these anomalies and prevent their inadvertent escape into an engine assembly. Current NDE techniques used include visual, fluorescent penetrant inspection (FPI), or an etching process, but they rely on line of sight inspections to detect these anomalies. These techniques may be inadequate due to part geometry.

The FAA New England Engine and Propeller Directorate initiated discussion with the propulsion industry through the auspices of the AIA Propulsion Committee to address machining processes and generation of related best practices. Conceptualization for this project is based on input from the industry, New England Directorate, and recent NTSB inquiries. An industry committee, known as ROMAN, has been established to address machining related issues. The ROtor MANufacturing (ROMAN) team was established to provide industry guidelines that improve manufacturing, engineering and quality practices towards eliminating manufacturing Induced anomalies in critical rotating parts[2]. A European program known as MANHIRP has identified the

[1] www.ntsb.gov

[2] "Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts", AIA Rotor Manufacturing Project Report, October 2002.

damage types resulting from various manufacturing event lapses[3]. Eleven defect types have been identified. ETC members are in contact with ROMAN participants and MANHIRP representatives in completion of this program. Given the need to detect and quantify the occurrence of anomalous machining damage, a four-stage program is planned as follows:

- Stage 1 – Fabrication and characterization of specimens: Members of MANHIRP have established fabrication processes to generate defects. ETC plans to purchase samples from MANHIRP members. Contingency plans also exist to use ETC facilities at the OEM partners to generate the specimens or subsets of the specimens as necessary. Upon delivery, samples will be characterized as necessary to document their as-received condition and to provide necessary input parameters for POD analysis as defined by the POD subteam.

- Stage 2 – NDE Preliminary Evaluation: A feasibility comparison will be completed for existing technologies. Several technologies have been identified by ETC members with additional technologies to be included as warranted from a literature survey to be performed as part of the program. A comparative matrix will be generated to quantitatively assess the performance of the selected technologies. A baseline set of specimens (three of each type + pristine specimen) will be provided to each technology provider. Based on results of the comparison of the baseline data, a subset of technologies will be selected for further development in Stage 3.

- Stage 3 – NDE Development: Optimization of selected technologies will occur initially using the baseline set to assess sensitivity improvements. After completion of the optimization process, a full specimen set will be provided for evaluation and to generate data for use in POD analysis.

- Stage 4 – Quantitative Assessment: A typical metric used in assessing inspection performance is the probability of detection (POD). However, the exact nature of the specimens, the distribution of their properties, and the disparate nature of their morphologies complicates the use of the traditional POD approach which is based on lcf cracks that are easily characterized. A POD subteam will provide guidance on sample characterization, NDE data acquisition, and data analysis to ensure that POD-related comparisons are available for those technologies that are developed in stage 3.

Objectives

- To identify and evaluate advanced NDE techniques that do not rely on visual inspections and are capable of detecting rotor disk surface and surface-connected, manufacturing-induced material anomalies that result from finish and semi-finish manufacturing processes.

- To refine the inspection process parameters for select techniques.

- To develop preliminary process specifications and associated POD curves.

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[3] Report Number MANHIRP-01-000006-WP1-RPT, 08 February 2001, Integrating Process Controls with Manufacturing to Produce High Integrity Rotating Parts for Modern Gas Turbines, Fox, K.M

Progress (through March 31, 2007):

Task 1: Develop Detailed Project Plan:

Subtask 1.1 – Project Planning:

The required Project plan was completed and submitted to FAA in November 2004. Revisions were made in November 2005. Updates will be made upon completion of the sample plan in cooperation with obtaining test samples from MANHIRP. A revised schedule is provided to the changes identified as Option A (See subtask 2.1 below).

Task 2: NDE Technique Evaluation and Selection:

Subtask 2.1 – Sample fabrication/acquisition:

MANHIRP Test Samples

No tangible activity has taken place to enable purchase of MANHIRP test samples for use under the ETC program.

ETC continues to pursue the risk management activity identified as "Option A" under the proposal. The remaining content of the quarterly report details progress made in this area.

NOTE: Option A is an FAA and ETC risk management plan that allows the program to proceed under a schedule that removes the acquisition of MANHIRP test samples from the critical path. Its objectives are not sufficient to complete the requirements of subtask elements 2.3-2.5. Completion of these subtask element will require a sufficient number of test samples to obtained (at a later date) through continued ETC fabrication or as purchased from MANHIRP.

ETC Test Samples - Option A

Within this reporting period the Option A activity was completed. A majority of the Ti 6-4 Option A activity was documented in the previous quarterly report and the entirety of In718 activity is documented herein. The progress and results of the fabrication efforts to produce anomalies for each of the machining methods are described below.

Under Option A, each OEM is responsible for fabricating anomalies to the following conditions and Table 1:

- Baseline test samples manufactured under nominal production quality.
- Type-1, Change to parent material continuous with the surface (microstructure damage, bent grain, white layer, amorphous layer, heat damage)
- Type-1*, Fabricated as Type-1, but lightly reamed to remove geometrical distortions, leaving material distortions present (NOTE: Hole test samples only)

- Type-6, Change to parent material discontinuous with the surface (re-deposited material, smearing of chips of parent material which bond back onto surface)

NOTE: The "Type" and characteristic of anomalies follows the same as identified under the MANHIRP program[3]

Fabrication of In718 Hole Test Samples

Within this reporting period, GE has completed fabrication of In718 hole specimens for Type 1, Type 1* and Type 6 anomalies, and using best practice parameters, produced damage-free baseline specimens. The anomalies were produced to a 7 mm diameter hole in 8 mm thick material. The manufacturing parameters used to fabricate the anomalies are identified below.

Limited details of the process conditions used to produce MANHIRP anomalies are available in public-domain documents. That information is consistent with prior GE experiments showing that certain holemaking process conditions can lead to the production of surface anomalies and a reduction in LCF performance:

- Poor tool condition, especially extreme wear or work material adhered to cutting edges and tool margins
- Inappropriate tool geometry, especially excessive margins or inadequate clearance angles
- Excessive cutting speed
- Lack of coolant

Consistent with prior experience, anomalies for the current program were produced using tools in poor condition, extreme cutting parameters, and in some cases, without coolant.

Like accomplished for Ti 6-4 test samples and described in the previous quarterly report, for each material and anomaly type, holes were initially machined in scrap material using practices expected to produce the intended levels of damage. Holes that appeared visually to meet the target criteria were then sectioned axially using wire EDM to allow closer examination of the hole surface and then mounted and polished to examine the microstructure.

When the process condition had been validated by metallography, the process was repeated by machining four to six holes in each of two bars to yield what would become the metallography and NDE specimens. Machining four to six holes made it possible to select two adjacent holes that exhibited the best representation of the target anomaly for metallography and NDE respectively. One pair of specimens (metallography and NDE) was harvested from each of the two bars.

Two LCF specimens were produced for each condition to validate that the anomalies were significant enough to reduce LCF performance, consistent with the earlier MANHIRP results. Two bars were also produced using the baseline process to provide an LCF reference for undamaged material at the test stress and temperature. It should be noted that two data points do not provide statistically significant results.

Although practices that produce damage in holes are known, producing specific anomalies typically involves more than a simple process formula. Programs of this nature require high levels of interaction from the test technician and result in some unsuccessful campaigns due to sudden catastrophic tool failure.

Non-damaged baseline holes were produced using machining practices typical of those used on production hardware including sharp tools, flood coolant, and speeds and feeds previously validated for surface integrity. These processes are codified in GE Special Process Specification P11TF12, *Processing of Holes in Critical Parts*.

Equipment Used and Machining

Holes were machined and fabricated in the GE Metalworking Technology Lab using the same equipment previously reported for the fabrication of Ti 6-4 hole anomalies.

Hole samples with no anomalies are machined using P11TF12-compliant cutting parameters previously demonstrated to have no negative impact on LCF properties. Except for variations in cutting speed, the same four-step process described below is typically used for all materials.

- Holes are rough drilled using sharp carbide tools, conservative cutting parameters and flood coolant. Spindle power is monitored to assure there are no un-noticed special cause events.
- Holes are finish reamed using sharp carbide tools, conservative cutting parameters and flood coolant. Spindle power is monitored to assure there are no un-noticed special cause events.
- A chamfermilling operation is typically used to edgebreak the hole entrance and exit, but due to the amount of displaced material produced during the heat-damage operations, a hand-fed plunge countersink operation was used instead. This approach was used on all of the samples for consistency.
- An abrasive brush operation is used on LCF specimens to break the sharp intersections that remain after the chamfer cut. This brushing operation also improves the surface finish of the hole body slightly. This process was also used to produce the baseline holes supplied for metallographic and NDE evaluation.

Samples with targeted anomalies were produced using specific process variations described in later sections for each alloy.

Metallography

The metallographic mounts for the In718 test samples were examined in a manner consistent with the same made for the Ti 6-4 hole test samples. Measurements were made along the axial surface of the hole at 20-100x. This orientation allows examination of the variation in the machined surface and underlying microstructure as a function of hole depth. Adhered/re-bonded material and Heat-Affected Zone (HAZ) depth are readily apparent in this orientation. Grain deformation depth can also be evaluated although the primary direction of grain deformation (the circumferential direction) is perpendicular to the plane of polish. The metallographic results were used to identify whether the target anomalies had been achieved and, in the case of the Type 1* condition, whether the damage was deep enough that it would still be present after reaming.

LCF Testing Description

LCF testing was performed using the same equipment previously reported for the fabrication of Ti 6-4 hole anomalies.

Load-controlled LCF testing was used to evaluate the hole specimens using the following test parameters:

- Triangular Wave Form
- R ratio = 0.01
- Frequency = 0.5 Hz
- Stress = 100 ksi

The Ti 6-4 specimens were tested at room temperature (RT) and 59 ksi alternating pseudo-stress while the In718 specimens were tested at an elevated temperature of 550 °C. These conditions were selected to best match previous MANHIRP test points.

Fabrication of Type 1 Anomalies in In718 With Holemaking Processes

Machining Parameters Used

Both loss of coolant and excessive cutting speed have been demonstrated in a number of past studies to eventually produce thermal damage in Inconel. Relative to the prior work in titanium, the number of holes generated before anomalous cutting begins is relatively consistent in Inconel and the holemaking processes are more repeatable. However in Inconel, once significant levels of heat are generated, the tool fails within just a few holes.

Also unlike titanium, significantly increasing the cutting speed (without coolant) leads to almost immediate drill failure and is not a sufficiently repeatable process. Conversely, heat builds very slowly over a large number of holes when drilling dry and using only modestly increased cutting speed.

Therefore, to minimize the number of holes required to achieve Type I anomalies, the feedrate/chipload was significantly reduced. This reduces the volume of the chip and its capacity to carry away heat, and increases the amount of time that the tool spends in the hole.

Specially modified drills were also employed. 0.281 inch diameter tools were circle-ground down to 7 mm diameter, producing wide margins without primary clearance and no back-taper. This increases the frictional heat generated by the sides of the tool. The tool material was also found to introduce variability and drills ground from K40UF carbide were used for all tests, the results of which are detailed in Table 1.

This strategy produced the desired level of thermal damage after four to seven holes.

Table 1. Process Parameters Used to Produce Type 1 Anomalies in In718.

Rough Drill	
Tool	Split-point, 2-flute, K40UF tungsten carbide, 30ºspiral-flute drill – 0.276 inch diameter
Cutting Speed	Inconel – 60 (sfm)
Feedrate	0.00025 inch per tooth (ipt)
Fluid Application	No cutting fluid

Methods Used for Control/Replication

An NC program was written to rapidly move the tool from a scrap plate to the specimen plate or LCF bar based on a command from the technician. When the technician observed that a given tool had begun to glow red (typically three to four holes) in the scrap plate the tool was switched to the specimen, where one to three holes were typically produced before tool failure. The power signal also correlates to the tool condition. An example of this progression in a scrap plate is shown. An example of this progression in a scrap plate is shown below in Figure 1 with the corresponding power monitoring output in Figure 2. Note the broken bit in the last hole of the lower row.

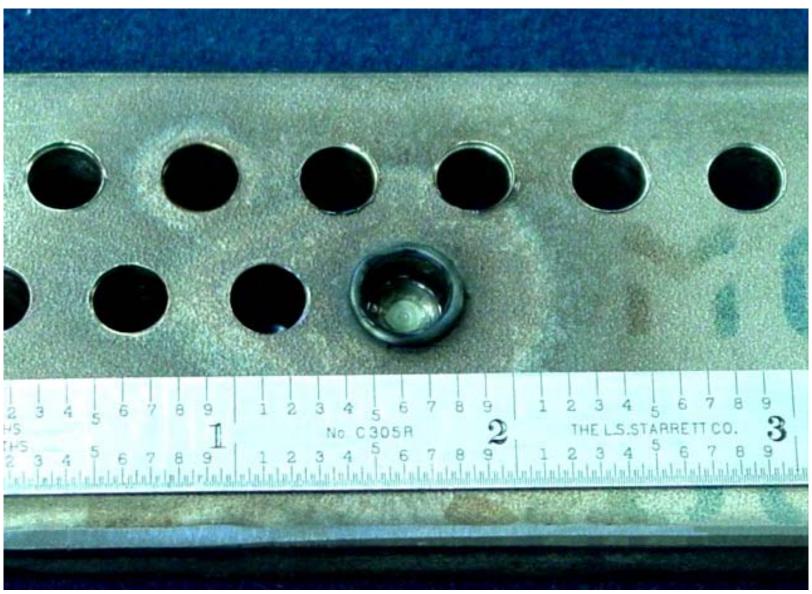


Figure 1. Successive progression of Type 1 hole with uneven heat conditions.

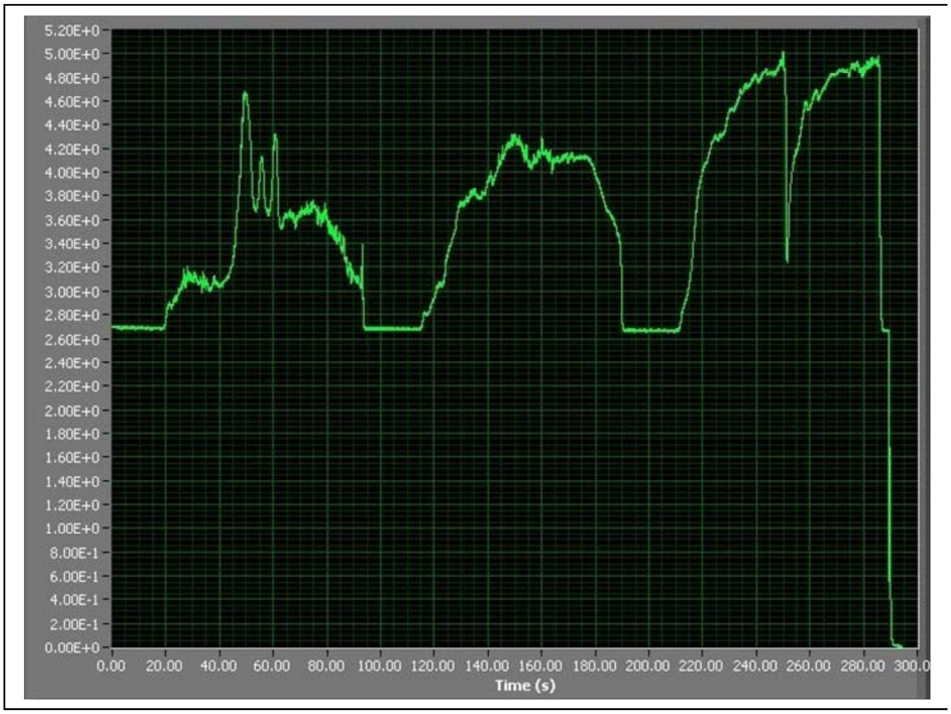


Figure 2. Power monitoring output of sample shown in Figure 1.

Holes with thermal damage in the range of 0.03 to 0.005 inch radial depth were consistently produced. The following photomicrographs show damage to the hole wall of the 4th (Figure 3), 6th (Figure 4), and 7th (Figure 5) holes produced by a particular tool.

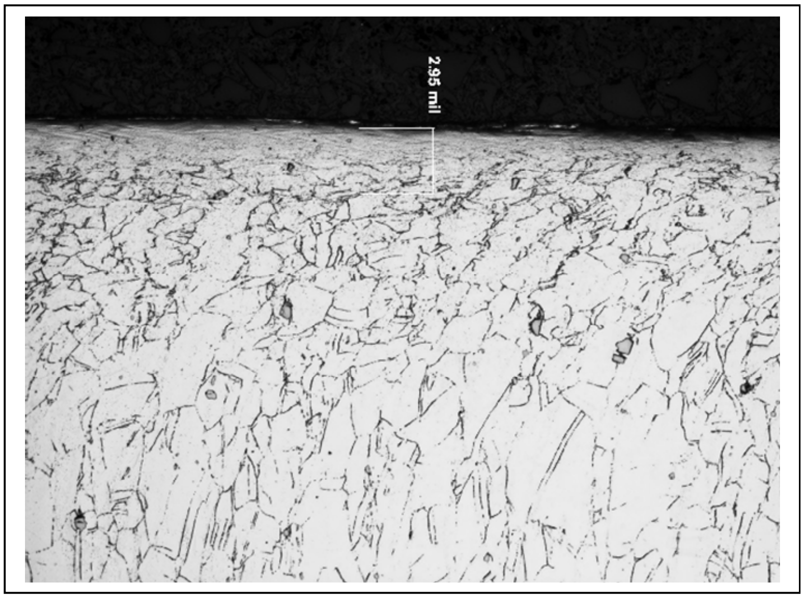


Figure 3. Micrographs of In718 Type 1 anomaly by hole process (hole #4), showing damage to a depth of 2.95 mils.

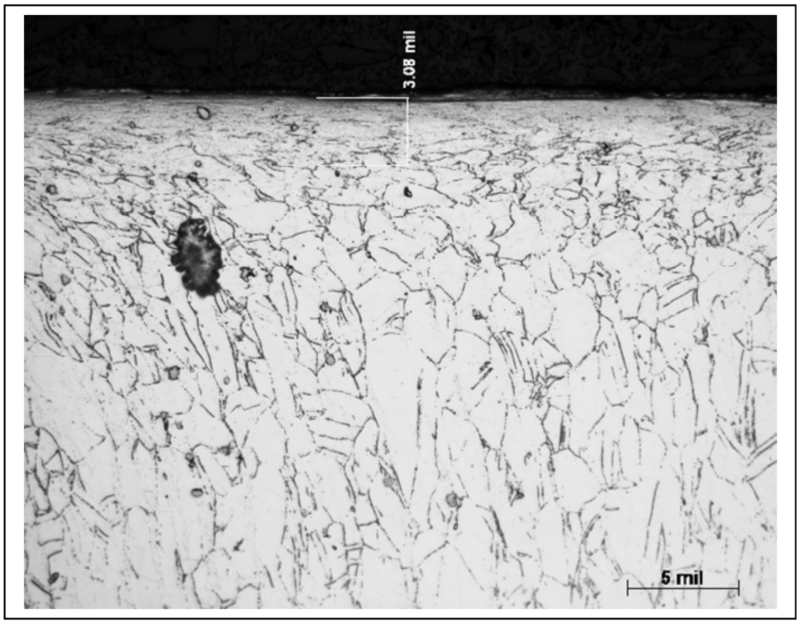


Figure 4. Micrographs of In718 Type 1 anomaly by hole process (hole #6), showing damage to a depth of 3.08 mils.

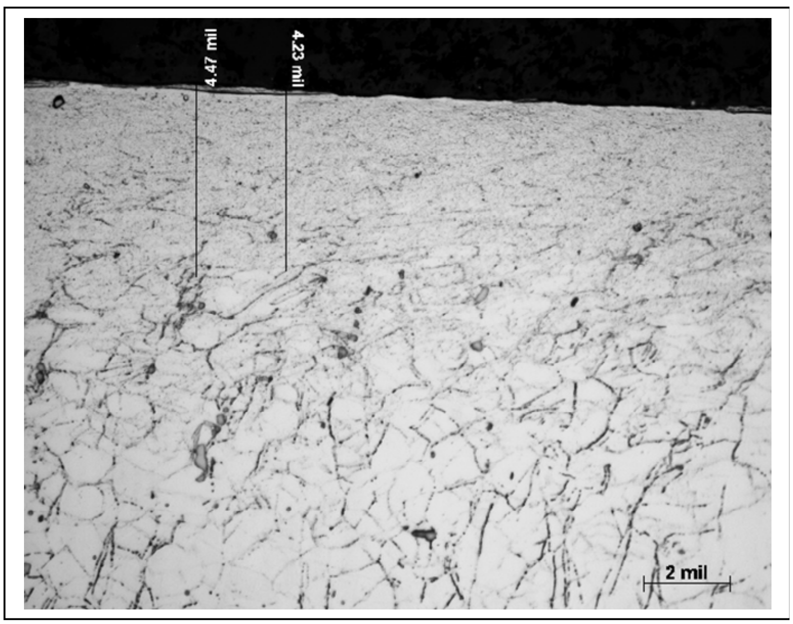


Figure 5. Micrographs of In718 Type 1 anomaly by hole process (hole #7), showing damage to a depth of 4.47 mils.

The damage depth can be very much larger near the exit of the hole (Figure 6) as shown for hole 7, although damage to the depth demonstrated on this sample was not common. Excessive depth of material damage is useful at this point to provide margin for removing material necessary to fabricate Type 1* holes.

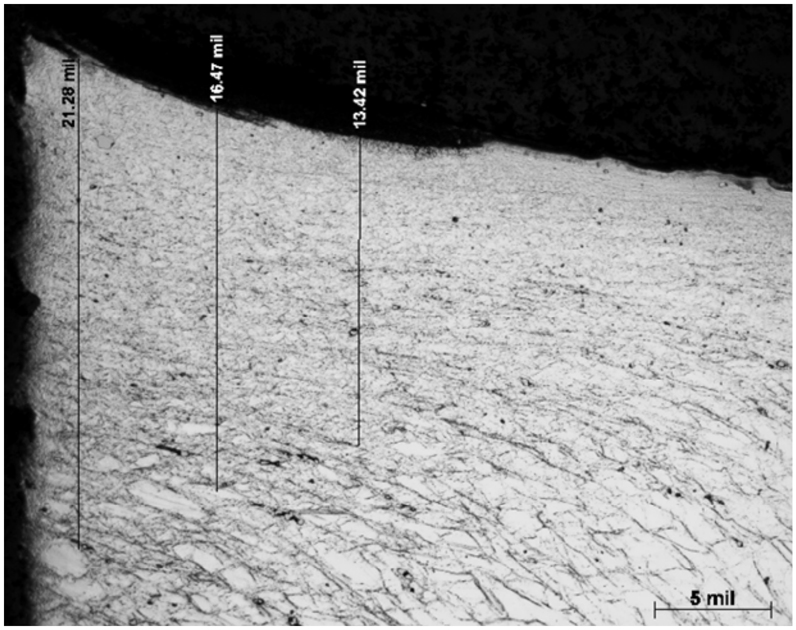


Figure 6. Micrographs of In718 Type 1 anomaly by hole process (hole #7 – Figure 5) showing excessive damage depth at the exit of the hole.

Summary Inconel Type 1 Anomalies - Holes

Producing Type I anomalies in Inconel was achieved using a combination of moderately elevated cutting speed, significantly reduced feedrate, and modified tooling run without coolant. The results are more consistent in Inconel than were previously obtained in titanium, but tool failure occurred rapidly at the levels of thermal input required to produce material damage to the target depth.

<u>Fabrication of Type 1* Anomalies in In718 with Hole Making Processes</u>

As with the Ti 6-4 hole test samples, Type 1* anomalies were produced by using typical best-practice finish machining processes to remove a surface layer from holes with deep Type 1 anomalies. The goal is to yield a surface which does not exhibit visible surface defects, but which retains some sub-surface metallurgical damage sufficient to negatively impact LCF performance.

Machining Parameters Used

Type 1 holes with significant thermal damage were finish machined to produce a Type 1* hole with a surface visually typical of an undamaged hole. Holes with large “volcano” burrs from the initial hot drilling operation were first manually deburred using a hand-fed plunge countersink operation and/or an abrasive disk. They were then finish machined using the same process used to produce defect-free baseline holes – reaming followed by edgebreak and an abrasive brush. A summary of the manufacturing process parameters is provided in Table 2 below.

Table 2. Hole Process Parameters Used to Produce Type 1* Anomalies in In718.

Machining Process used to Produce Anomaly-free Holes	
Rough Drill	
Tool	Split-point, 2-flute, tungsten carbide, spiral-flute drill – 0.271 inch diameter
Cutting Speed	Inconel – 60 (sfm)
Feedrate	Inconel – 0.00025 (ipt)
Fluid Application	None
Finish Ream	
Tool	6-flute, tungsten carbide, 15º helix reamer – 7mm (0.2756 inch) diameter
Cutting Speed	Inconel – 35 (sfm)
Feedrate	Inconel – 0.001 (ipt)
Fluid Application	Flood coolant
Edgebreak	
Tool	100º, tungsten carbide, single-flute plunge countersink
Cutting Speed	7.2 (sfm) plunge countersink
Feedrate	Hand Feed
Fluid Application	Flood coolant
Chamfer Corner Rounding	
Tool	Brush Research “Flexhone”, SiC, sized for 0.276 hole
Cutting Speed	65 (sfm)
Feedrate	50 (ipm)
Fluid Application	Flood coolant

Methods Used for Control/Replication

GE’s P11TF12 Holemaking specification requires at least 0.006 inch radial material removal (0.012 on the diameter) using finish machining operations after rough drilling on most holes. However, metallographic examination of early test holes showed that the maximum thermal damage layer would be completely removed by this level of finish machining.

To assure that sufficient thermally damaged material remains in the holes, the reaming amount for this program was reduced to ~0.002 inch per side. Metallography was performed on a series of Type 1 holes and it was determined that the typical damage depth of approximately 0.004 prior to ream would be sufficient for a 0.002 inch ream. Unlike the titanium samples, the 0.002 inch depth-of-cut was sufficient to provide a good visual surface condition. (Figure 7 through Figure 9).

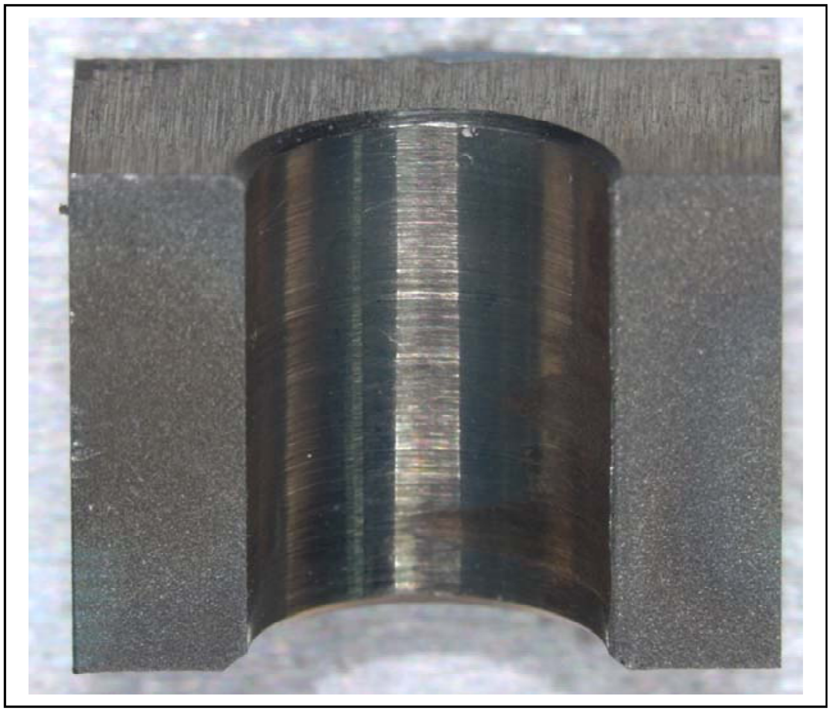


Figure 7. Resulting post-finished surface in In718 hole test samples for Type 1 anomalies.

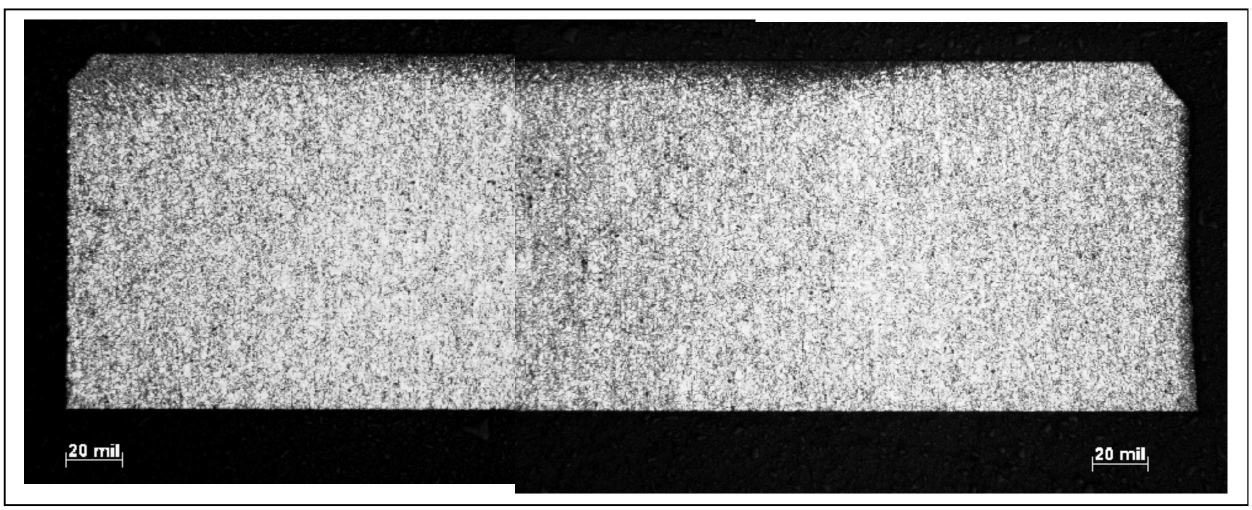


Figure 8. Micrographs of In718 Type 1* anomaly by hole process, showing remaining material damage post-finishing.

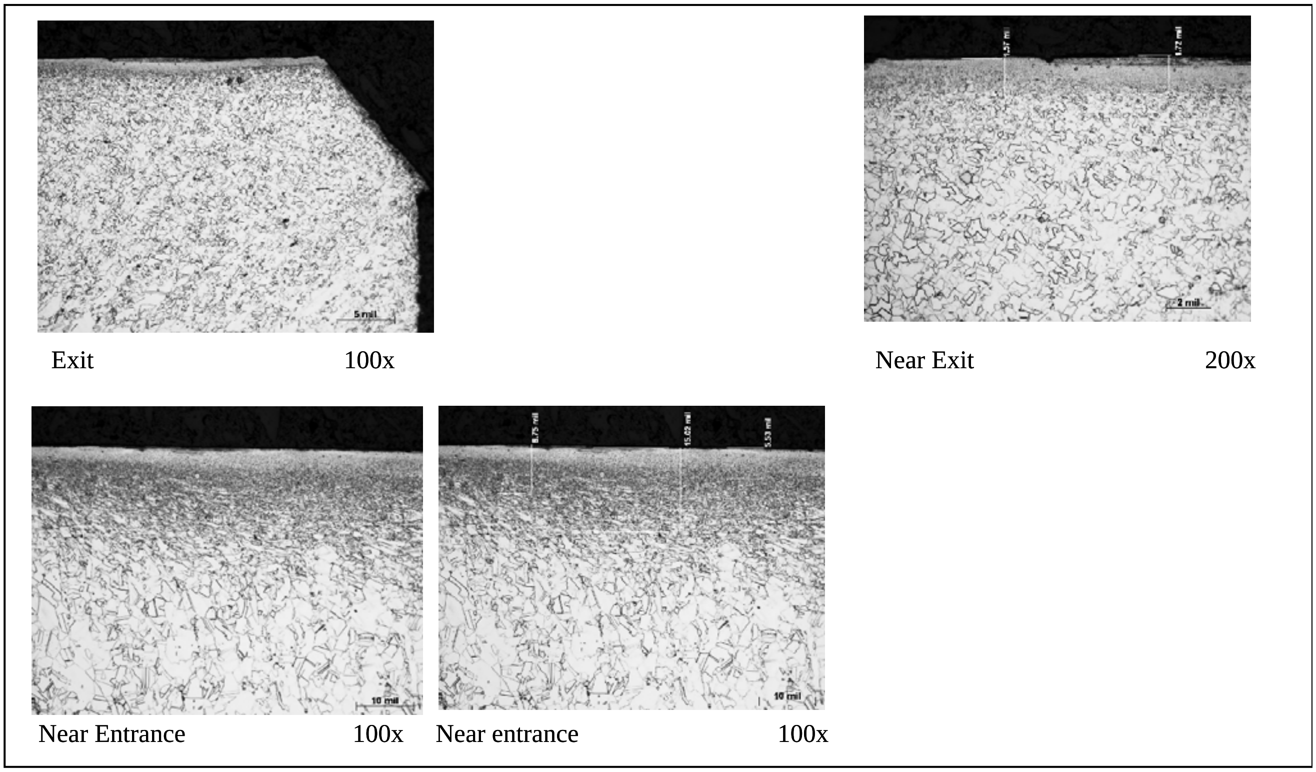


Figure 9. Additional micrographs of In178 Type 1* anomaly by hole process, showing remaining damage material structure.

Summary Inconel Type 1* Anomalies - Holes

Production of the Type 1* anomalies confirms that it is possible to produce thermal damage in a Inconel hole yet finish machine that hole to a condition that would pass visual inspection. Type 1* samples are straight-forward to produce from Type 1 holes.

Fabrication of Type 6 Anomalies in In718 With Hole Making Processes

Type 6 anomalies require the machining operation to produce discontinuous smearing and gouging without substantial thermal damage. The difficulty from a machining practice standpoint is that most of the physical cutting conditions that produce the desired smearing also produce heat energy. A strategy was employed using tools modified to induce rubbing, moderately aggressive machining parameters, and flood coolant to limit thermal damage.

Holes are machined in a scrap plate in the same manner as for Type 1 anomalies until the tool exhibits severe adhered material/ built-up-edge on the cutting edges and margins. The process parameters are then reduced and the last hole produced in the scrap plate is examined to assure it exhibits the desired level of anomalies.

The tool is then used to produce holes in a six-hole or LCF specimen as described earlier for Type 1 processing. Entrance and exit edgebreak are applied. The NDE and metallographic samples receive a light manual shoestring operation to remove the edgebreak burr, but the holes are not reamed or finished with an abrasive brush. The LCF bars receive a light abrasive brush operation to remove any chamfer burrs since these burrs are demonstrated to have a significant impact on LCF results.

Machining Parameters Used

The Type 6 holes do not receive any finish machining so the drill is sized at the target final diameter of 0.2756. To increase the rubbing action on the hole walls, the test drills are circle - ground down from 0.281 diameter to create wide, low-clearance margins with no back-taper.

The drill is preconditioned using the same elevated speed / reduced feed parameters used to produce Type 1 anomalies, but once adhered material is noted on the tool the parameters are reduced to those noted in order to produce the required Type 6 anomalies. Running at these less aggressive parameters, the process is stable and will produce six or more Type 6 holes without tool breakage. A summary of the manufacturing process parameters are provided in Table 3 below.

Table 3. Hole Process Parameters Used to Produce Type 6 Anomalies in In718.

Rough Drill	
Tool	Split-point, 2-flute, tungsten carbide, 30ºspiral-flute drill – 0.276 inch diameter with modified low-clearance margins and low back-taper. Pre-conditioned to produce visible adhered work material.
Cutting Speed	Inconel – 20 (sfm)
Feedrate	0.0002 inch per tooth (ipt)
Fluid Application	No cutting fluid
Edgebreak	
Tool	100º, tungsten carbide, single-flute plunge countersink
Cutting Speed	7.2 (sfm) plunge countersink
Feedrate	Hand Feed
Fluid Application	Flood coolant

Methods Used for Control/Replication

Drills are used to machine holes in a scrap plate without coolant until significant material build-up is noted in Table 3 on the tool. This is indicated by changes in the power signal and by evidence of heat building at the exit of the hole. The tool is then removed and examined for the condition of the cutting edges and margins. If significant adhered material is noted and the last holes in the scrap plate show smearing the tool is then used to produce specimen holes for metallography, NDE, or LCF. An example of a tool with significant adhered material is shown in

Figure 10 below. Figure 11 provides surface photographs of a smeared hole showing the Type 6 anomaly with micrographs shown in Figure 12 and Figure 13.

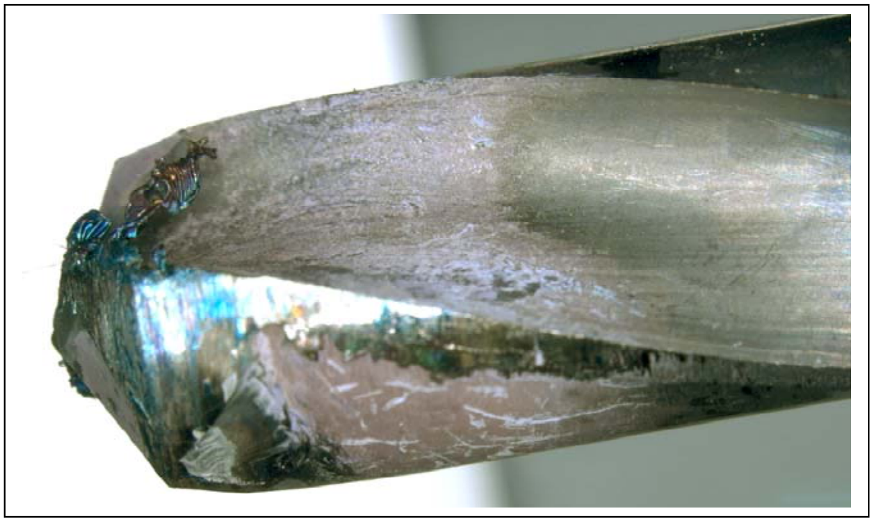


Figure 10. Example of a tool with significant adhered material. This tool was used to fabricate Type 6 anomalies in In718.

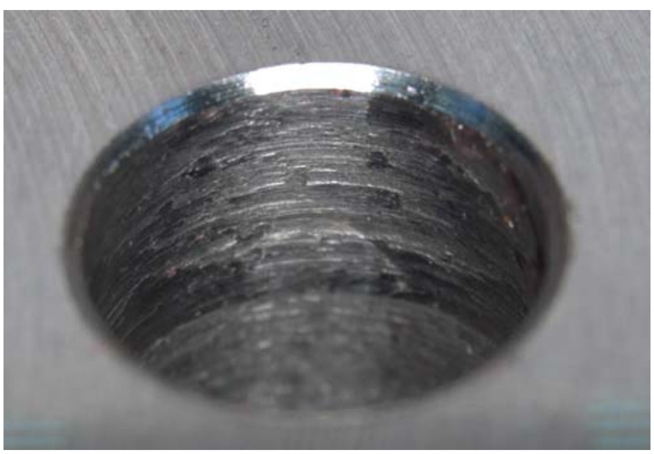


Figure 11. Surface photographs of smeared hole material – Type 6 anomaly.

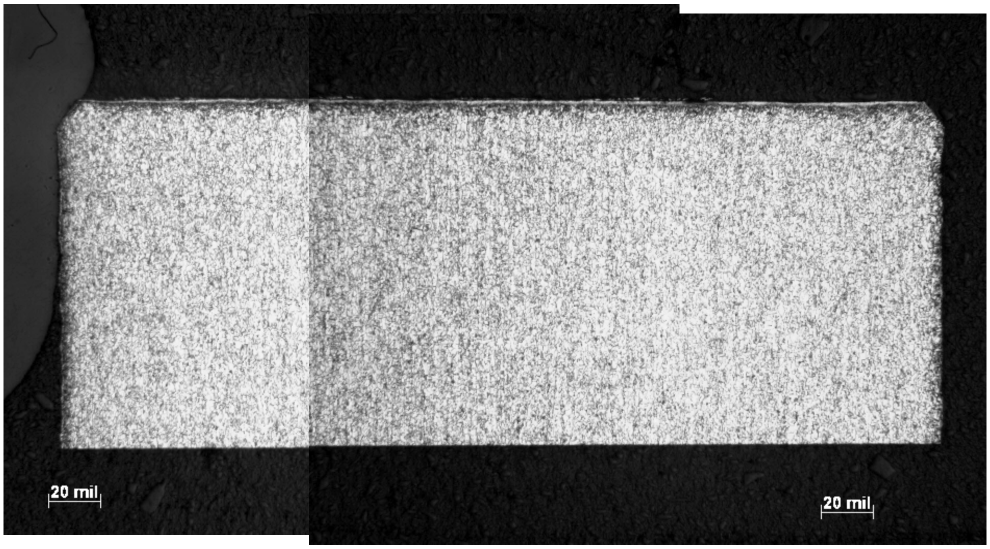
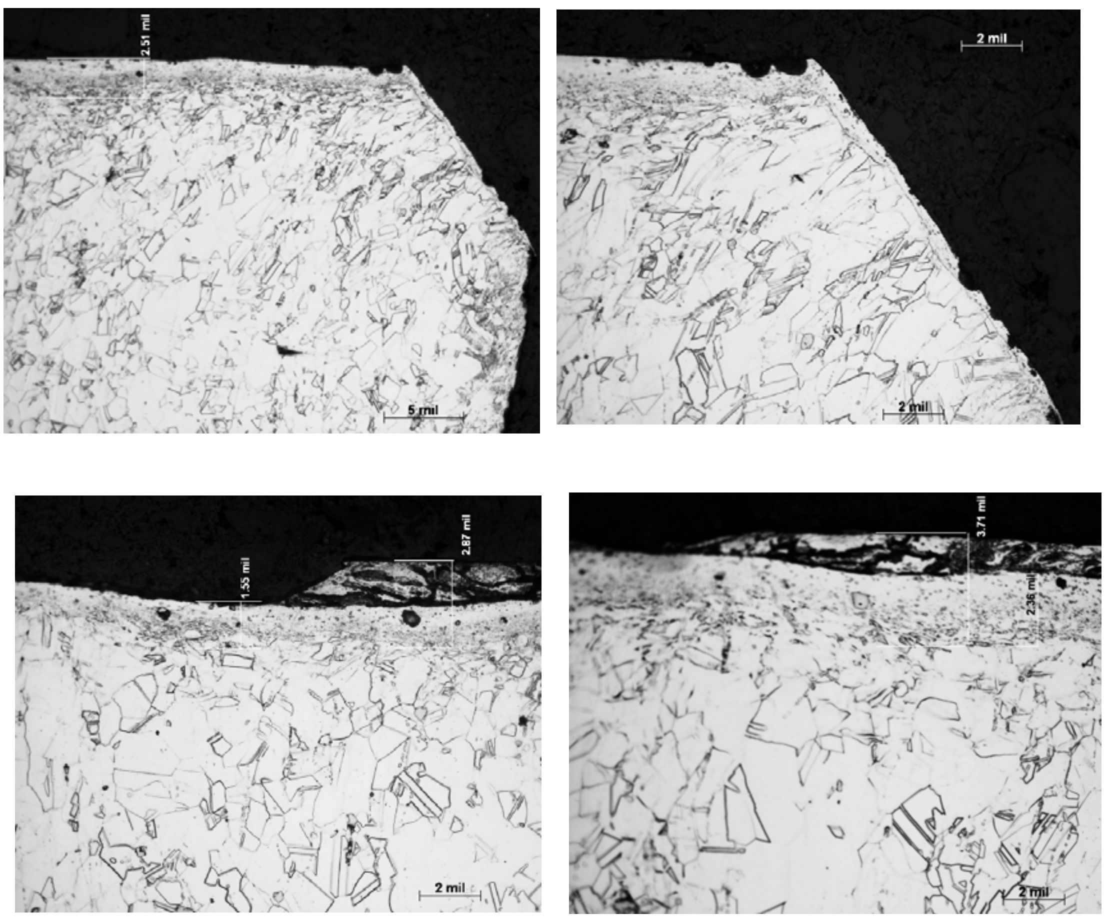


Figure 12. Micrographs of In718 Type 6 anomaly by hole process of Figure 11.



Near Entrance 200x   Midspan 200x

Figure 13. Additional micrographs of In718 Type 6 anomaly by hole process, showing remaining damaged material structure from metal smearing.

Summary In718 Type 6 Anomalies - Holes

The use of custom sub-optimal tool geometry and dry machining to pre-condition the tool reduces the time necessary to generate a tool condition that produces Type 6 anomalies. Power monitoring can provide a useful real-time indication of whether the desired process conditions have been achieved. Compared to previous work in titanium, Type 6 anomalies in Inconel can be produced consistently once a tool has been properly pre-conditioned.

LCF Results Anomalies in In718 with Hole Making Processes

LCF specimens were produced to validate that the damage noted by metallography was of a nature and severity that it would negatively impact LCF performance. The LCF results are shown below in Figure 14. Since a fatigue debit was demonstrated to be similar to that obtained by MANHIRP and by ETC for the Ti 6-4 hole test samples, a complete baseline testing to failure was not accomplished.

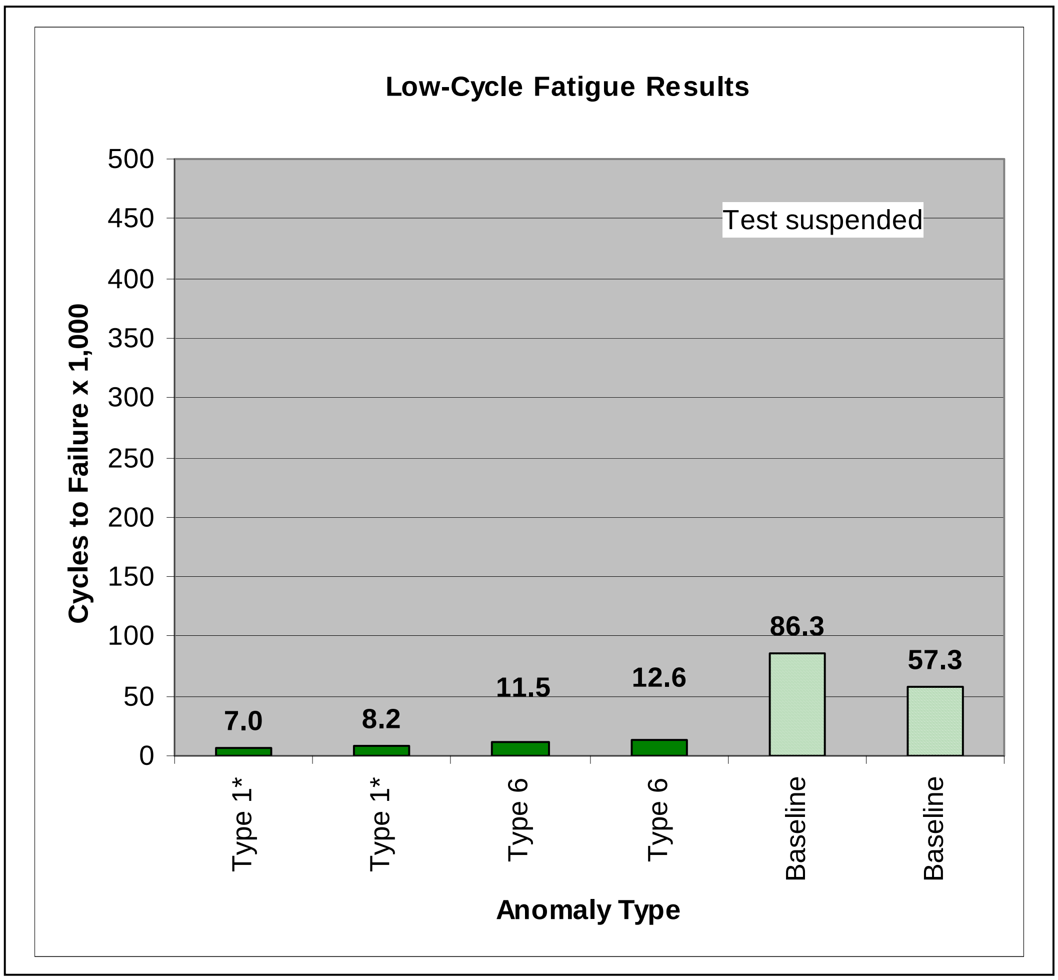


Figure 14. Comparison of the LCF Testing Results for In718 Hole Samples Containing Baseline, Type 1* and Type 6 Anomalies.

Summary In718 Hole Making Processes

Holes with Type 1, Type 1* and Type 6 anomalies have been successfully produced in Inconel. The anomaly conditions have been verified by metallographic examination and the impact on material properties has been demonstrated by Low Cycle Fatigue testing. Damage-free baseline holes have also been produced and verified.

Processes have been developed and documented to produce the Type1, Type 1* and Type 6 anomalies, as well as damage-free baseline holes. The processes to produce the anomalies are subject to variability and require attentive interaction from the test technician. This is consistent with several prior test campaigns within GE Aviation and with observations reported by participants in the MANHIRP program.

LCF Results - Anomalies in Ti 6-4 with Turning Processes

In the previous reporting period, the production of Type-1 and Type-6 anomalies in Ti-6-4 plates was described. The associated LCF samples had been produced, but the tests had not been performed until this reporting period.

Three samples had been produced for the pristine condition, i.e., with nominal machining parameters and no defects. The first two samples were tested in the LCF rig, but unfortunately they broke prematurely on the short sides of the sample rather than on the face with the turned surface that was to be tested. The third sample was shot peened on the short sides to force the failure to the intended surface. The method worked and ran to the expected life. This made only one sample to use for the baseline condition. However, the very high debit in life exhibited by the samples with defects, both Type-1 and Type-6, negated the need to average over multiple baseline samples. Even if a second baseline sample had only 50% of the life of the one that was tested, a degree of variation that is possible in LCF testing, the debit displayed by the defect samples would still be very large. Figure 15 shows the plot of the LCF results comparing the two Type-1 and two Type-6 samples with the baseline sample. The defect samples were prepared in the same fashion as the pristine sample with shot peened sides. A summary of the LCF parameters is provided in Table 4 below.

Table 4. Parameters Used for LCF Testing of the T-6-4 Turn Test Samples.

Temperature	70^{o}F (21^{o}C)
Frequency	1 Hz
R-ratio	0.05
Loading	Load controlled

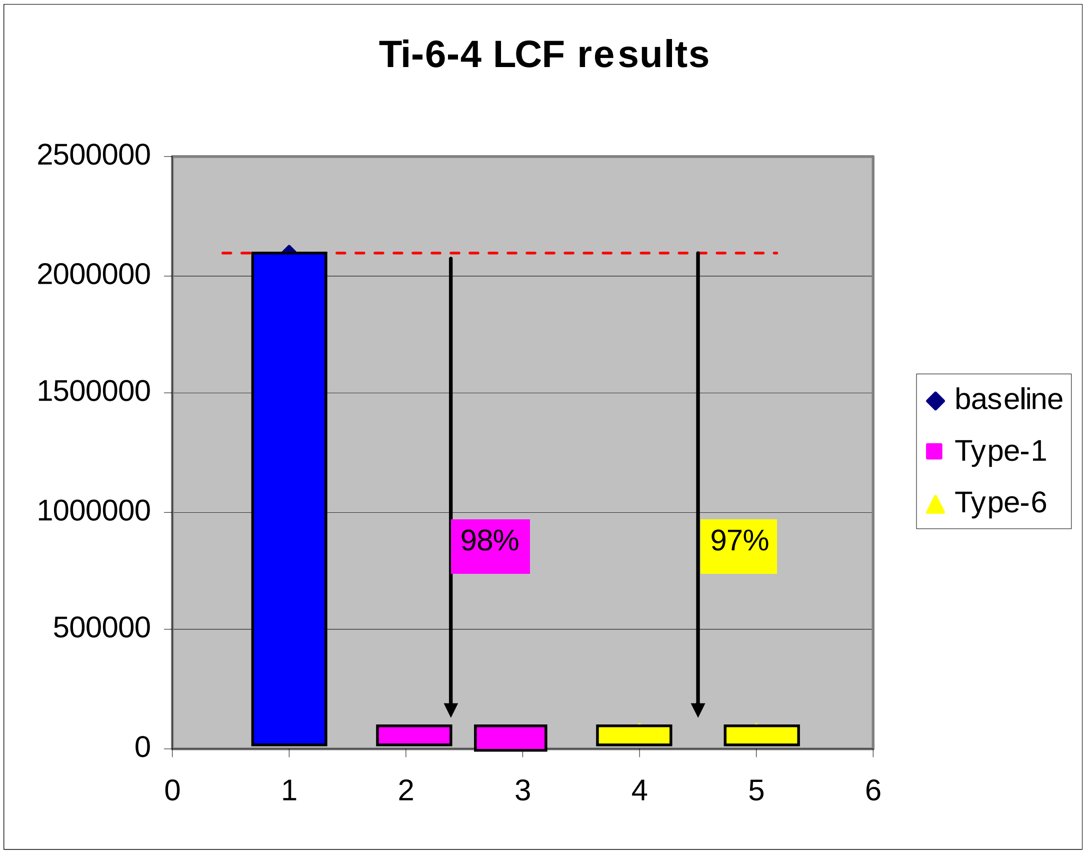


Figure 15. LCF Results for Ti-6-4 Samples Produced by Turning in the Baseline Pristine Condition and With Type-1 and Type-6 Anomalies.

Fabrication of In718 Turn Test Samples

Turning of In718 to produce defects of Type-1 and Type-6 was performed using material that was supplied in pancake form. The pancakes were forged and heat treated to typical rotor grade microstructure. The pancake was sectioned to produce washer shapes that could be used on the same vertical turning lathe that was used for the Ti-6-4 machining trials. Figure 16 shows the sectioning layout for the washers and how the LCF and NDE samples were sectioned after trials were completed.

Table 5 shows a summary of the machining conditions used to produce the pristine samples and the variations used to produce defect samples. For the washers used in this machining study, the ID was 7" and the OD was 12.5" so the mid-diameter was 9.75". The machinist reported the RPM that the machine was set for and the surface speed is shown for the mid-diameter.

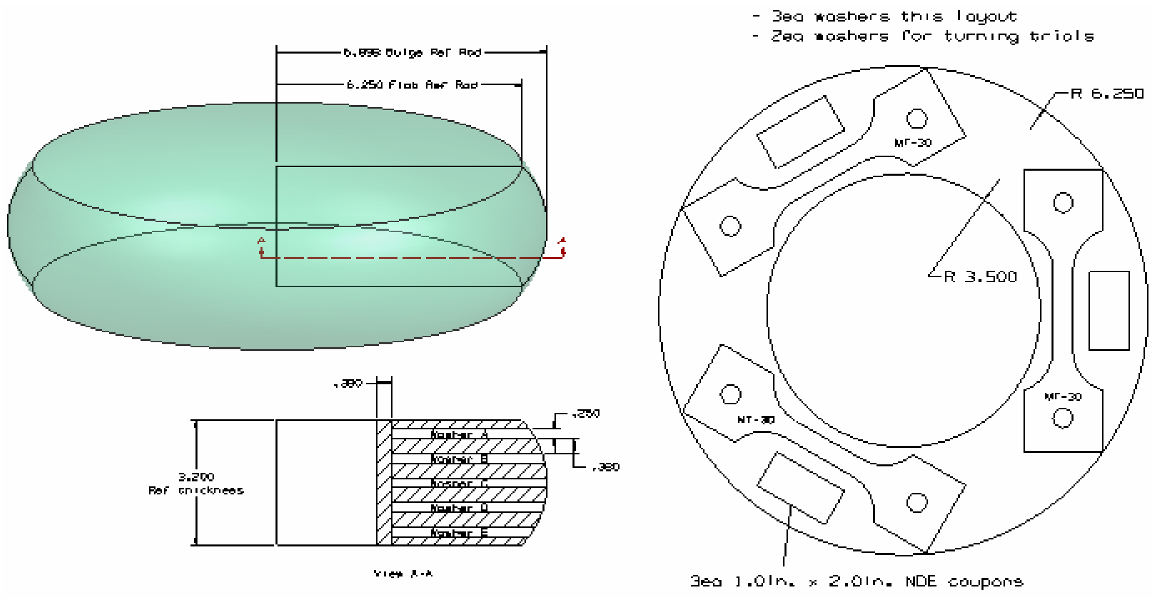


Figure 16. Sectioning of In718 Pancake to Produce Turn Test Samples.

Fabrication of Type 1 Anomalies in In718 with Turn Processes

For Type-1 anomalies, it was known from the MANHIRP literature that turning speed was the major factor in producing anomalies with TiN coated carbide cutting tools. Even so, the distorted layers reported were less than 1 mil and the amorphous layer was not consistent. Similar results were found in the current trials at PW to create Type-1 anomalies.

Table 5. Machining Parameters Used for Manufacturing Turning Anomalies.

Test	Speed (RPM)	Surface speed at washer average radius	Feed rate	Depth of cut	coolant	Tool condition
A (pristine)	16	40.8 ft/min	0.006 in/min	0.010”	Yes	New
B	23	58.7 ft/min	0.006 in/min	0.010”	Yes	Dull
D	6.5	16.6 ft/min	0.012 in/min	0.005”	No	Dull

The excessive amount of material required for machining trials did not allow for further testing, but success was observed for the B test washer. The same parameters were applied to washer C to produce the LCF and NDE samples and further metallography was performed on samples from washer C to verify the presence of the disturbed microstructure that denotes Type-1 defects. Figure 17 shows the microstructure of the pristine material from washer A from which the LCF and NDE baseline samples were made. Figures 18 and 19 show the microstructures of test washer B and washer C respectively. It is apparent that the desired anomaly was produced in both pieces.

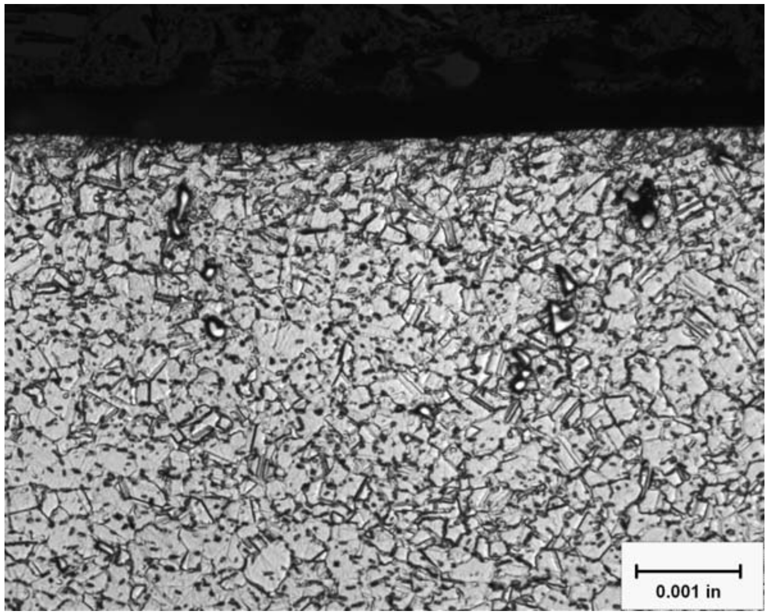


Figure 17. Microstructure of Nominal In718 Material without Machining Anomalies.

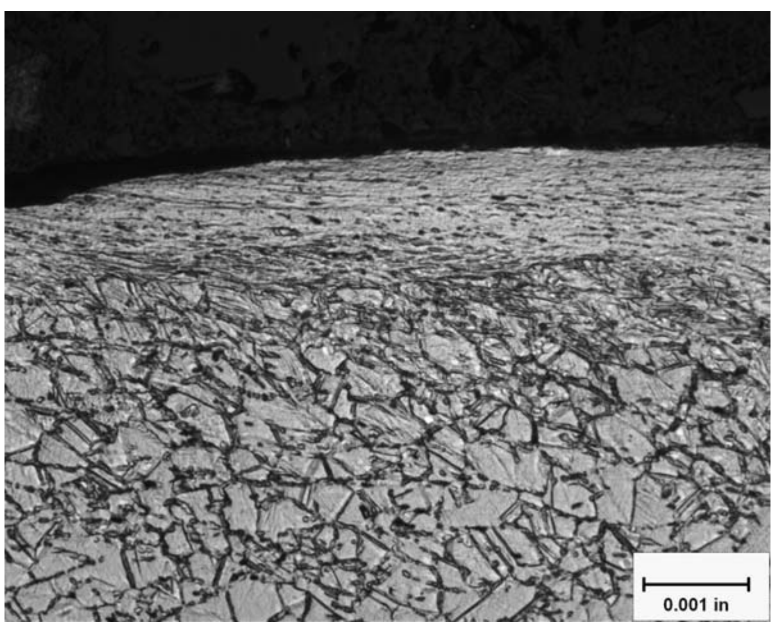


Figure 18. Microstructure of Type-1 Anomalies in Test Washer B.

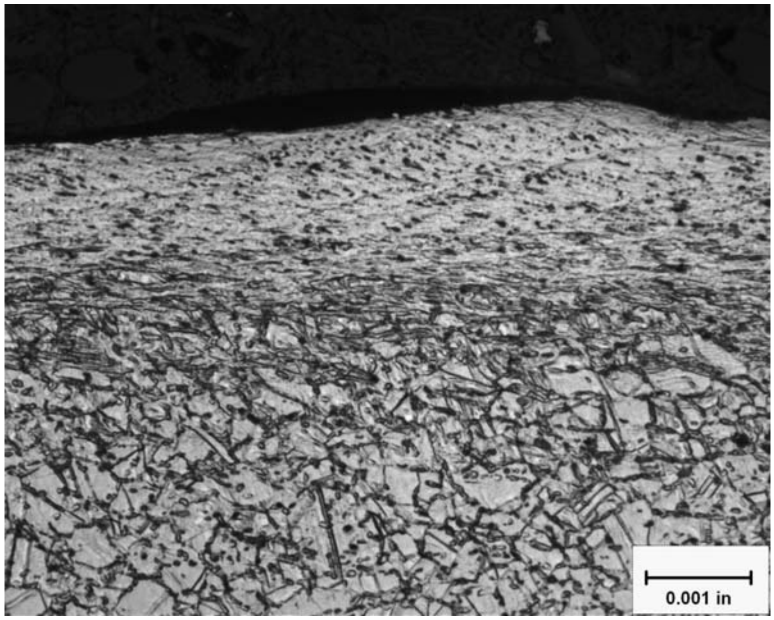


Figure 19. Microstructure of Type-1 Anomalies in Washer C Used to Make LCF and NDE Samples.

It is evident from Figure 20 that parameters used for test washer D did not produce the desired amorphous layer and distorted grain structure of Type-1 anomalies.

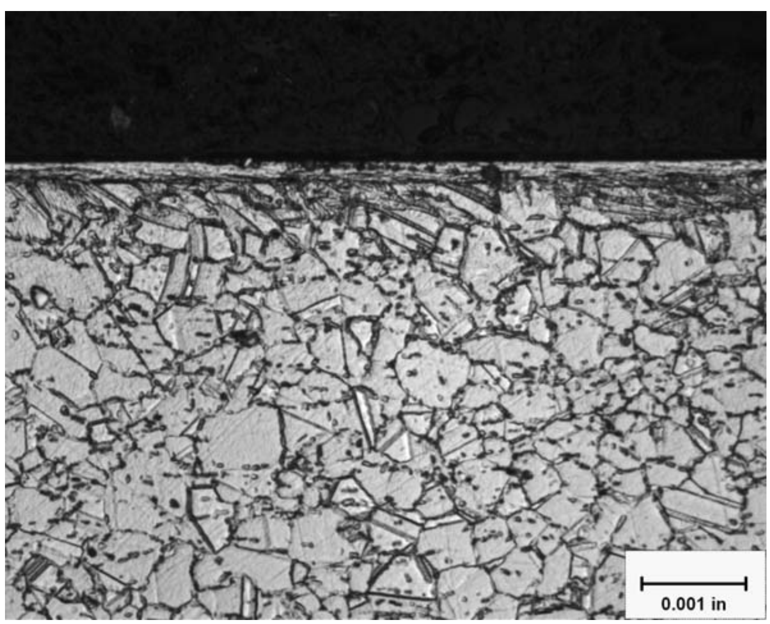


Figure 20. Microstructure of In718 Test Washer D.

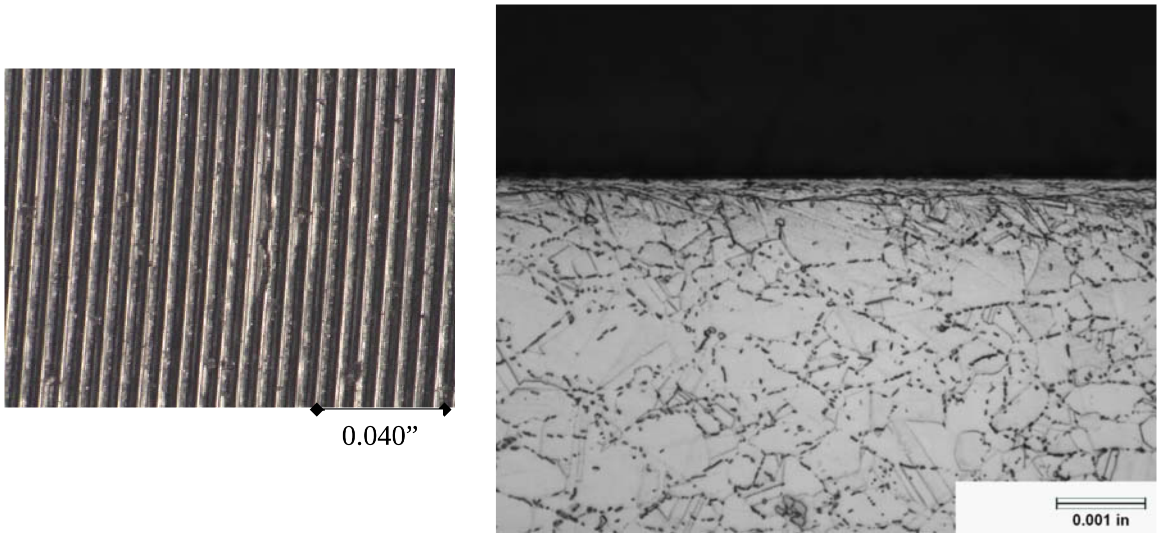
Fabrication of Type 6 Anomalies in In718 with Turn Processes

Type-6 anomalies in turning consist primarily of re-embedded material due to chips that are not removed adequately during machining. To produce such a condition in the limited material available for trials, chips were introduced into the cutting path and coolant was turned off to prevent removal of the chips. Table 6 shows the parameters used to make the Type-6 trials and the nominal conditions of the pristine sample are shown again for comparison.

Table 6. Parameters Used for Pristine Samples and for Type-6 Anomalies.

Test	Speed (RPM)	Surface speed at washer average radius	Feed rate	Depth of cut	coolant	Tool condition
A (pristine)	16	40.8 ft/min	0.006 in/min	0.010”	Yes	New
6-1	31	79 ft/min	0.006 in/min	0.040”	No	Dull
6-2	31	79 ft/min	0.006 in/min	0.015”	No	Dull

The 6-1 washer used a very large depth of cut which makes for a rough surface unless a skim cut is applied to make it smoother. The parameters also did not provide a consistent occurrence of embedded material as is observed in the Figure 21. While there appears to be a small amount of embedded material in the surface image, the transverse micrograph shows that the material was likely lost during sectioning.

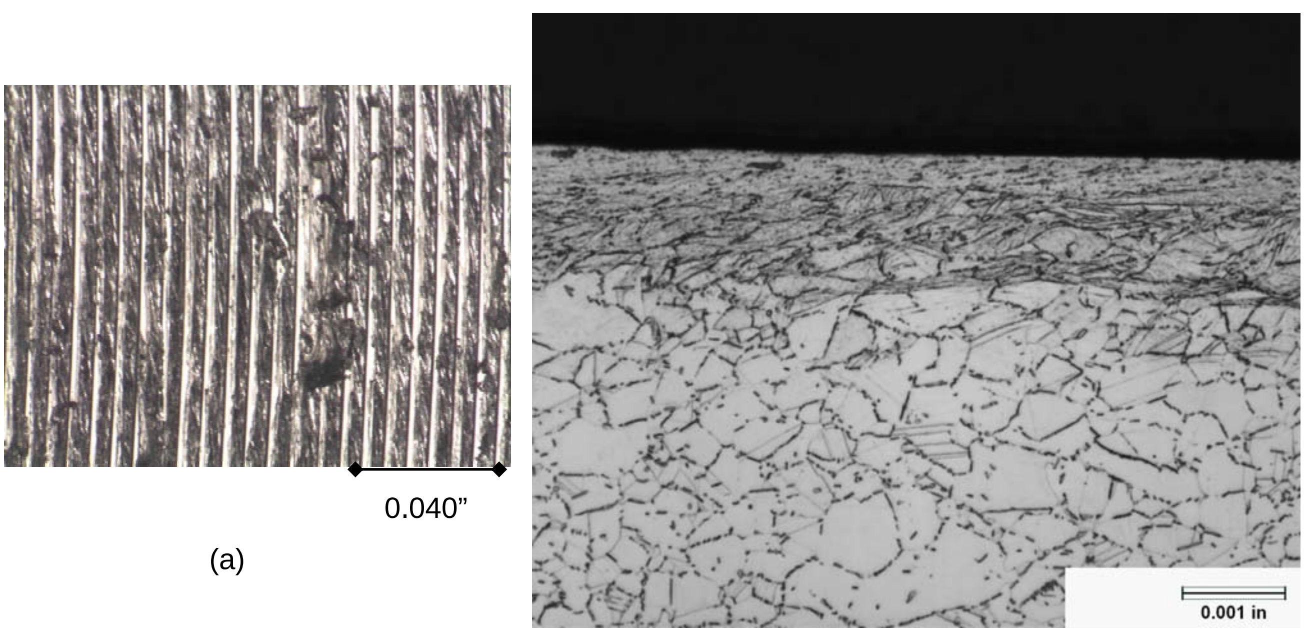


(a)

(b)

Figure 21. (a) Surface Image and (b) Microstructure of Sample Washer 6-1.

The 6-2 washer did provide the condition of embedded material as can be seen in Figure 22. The parameters for washer 6-2 were used to produce LCF and NDE samples for the Type-6 defects.



(a)

(b)

Figure 22. (a) Surface Image and (b) Microstructure of Washer Sample 6-2.

LCF Results Anomalies in In718 with Turn Making Processes

LCF testing was performed for two each of the pristine samples, the Type-1 samples, and the Type-6 samples. The testing was performed with the parameters shown in Table 7.

Table 7. Parameters Used for LCF Testing of the In718 Turn Test Samples.

Temperature	1022°F (550°C)
Frequency	0.167 Hz
R-ratio	0.05
Loading	Load controlled

As depicted in Figure 23, the samples with defects showed a very high life debit as compared to the pristine samples prepared for this test. All samples were prepared in the same fashion where the edges of the samples were peened as well as having the grips peened.

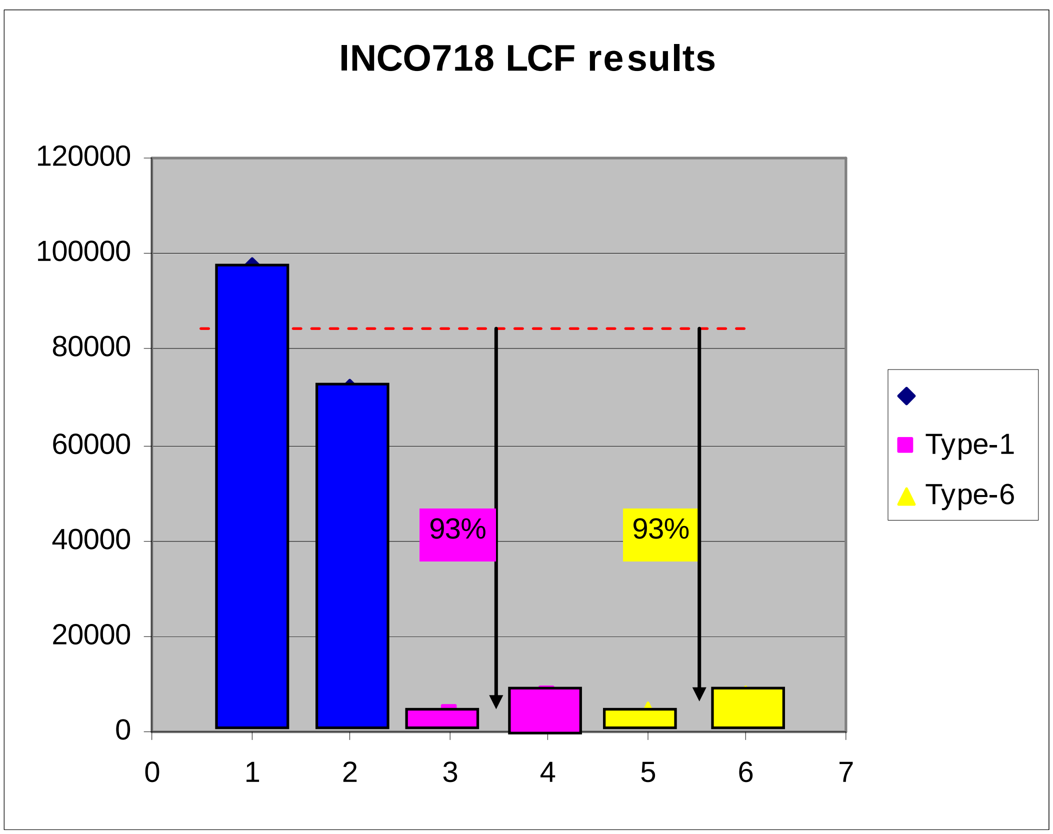


Figure 23. Result of the LCF Tests Performed for Turned Samples of In718.

Summary In718 Turn Making Processes

It was demonstrated that for both Ti-6-4 and In718, the two defect types of interest could be produced in test samples and in LCF samples. Coupons with a surface area of 1" x 2" were prepared for eventual testing with NDE techniques. The parameters, however, still require refinement to be able to produce samples with varying degrees of severity. One possibility for such samples is to produce washer shapes that are known to have very deep layers of defects and then to skim cut the surface to achieve different thicknesses of defects. Some further refinement of machining parameters is expected before initiating production of the full set of NDE test coupons.

Fabrication of In718 Broach Test Samples

Broach specimens in In718 material were produced at the Honeywell Rotating Hardware Center of Excellence (COE). The target anomalies were Type 1 and Type 6 of the non-geometric material anomalies as previously defined by the MANHIRP consortium. Type 1 anomalies are described as a "Change to parent material continuous with surface," and Type 6 anomalies are described as a "Change to parent material discontinuous with surface." In addition samples were manufactured using nominal production manufacturing conditions to create baseline "pristine" specimens. The broaching trials for In718 were conducted in 3 phases:

- Phase 1- manufacturing of baseline "pristine" samples
- Phase 2- Designed experiments to determine the effect of broaching parameters on manufacturing induced anomalies
- Phase 3- Manufacturing of samples with targeted anomalies.

After the pristine samples were machined, NDE, Metallographic, and LCF specimens were manufactured. An iterative process of broaching specimens and evaluation of the broached specimens was employed to study a full range of parameters. The broached specimens were evaluated visually, metallographically, and with Scanning Electron Microscopy (SEM).

A 6 inch sample length was used for elevated temperature LCF testing, and a 3.4 inch sample length was used for metallographic and NDE samples. The extended length of LCF specimens was employed to readily accommodate the heating elements required for the elevated temperature testing. The 3.4 inch length was used for the other samples to maximize the number of samples that could be extracted from the In718 forging.

Equipment Used

All broaching was performed on a production 15-180-HE Detroit Horizontal broach machine in the Honeywell Rotating Components COE. This machine is capable of cutting at speeds up to 22 ft/min. The fixture used to hold samples and parts during broaching is equipped with a vibration monitoring system. The system gives an indication of tool wear, coolant flow, and aggressive depth of cuts.

A Nikon D1 digital camera was used to document the condition of the dulled / worn cutting tools. Metallographic samples were prepared on standard metallographic equipment and a Reichert

Jung optical microscope capable of 16X to 1000X magnification was used to evaluate the samples. A Jeol JSM6460 SEM was used to characterize the surface of the broached samples.

Machining

The following manufacturing conditions/settings were evaluated for their effect on the broached surface:

- Cutting speed (2ft/min – 22 ft/min)
- Cooling of samples (coolant on – coolant off)
- Tool sharpness (sharp cutting edge – rounded cutting edge)
- Crown cutter tool offset (0.000 – 0.015")
- Carbide form cutter offset (0.000 – 0.015")

The baseline "pristine" samples were broached using typical production conditions and settings as follows:

- Cutting Speed: 5 ft/min
- Coolant: ON
- Crown Cutter cutting edge: Sharp
- Carbide Form Cutter edge: Sharp
- Tool offset: None

Once the baseline NDE, metallography, and LCF sample blanks had been manufactured, a series of three broaching trials were conducted. The first broaching trial was used to study the effect of cutting speed and coolant flow when broaching with sharp tooling. The final form carbide insert was removed to prevent it from "cleaning up" any anomalies created by the final crown cutter tool segment. The second trial was used to study the effect of cutting speed, coolant flow, and tool offset when broaching with a dulled tool. The final form carbide insert was removed for this trial as well. The third trial was conducted to evaluate the effect of cutting speed, coolant flow, and offset of the final carbide insert form cutter. The specific broaching parameters used to create the deliverable samples with anomalies are described in the subsequent appropriate sections of this report.

Metallography

The broached samples were sectioned so that the polished surface was parallel to the broaching direction and down the centerline of the slot through the crown. This sectioning orientation allowed evaluation of the variation in microstructural damage as a function of position relative to the broach tool entrance and exit. Amorphous layer thickness and grain deformation depth were readily evaluated when using this sectioning orientation.

Samples were mounted in Bakelite. The polished samples were etched with Kallings and evaluated at magnifications between 16X and 500X.

LCF Test Description

LCF testing was performed on a MTS servo hydraulic system with a 10-KIP test frame. MTS hydraulic wedge grips (Model 647) were used to hold the test specimens. The temperature of the specimens was controlled using resistance element heating with a Yokogama controller and Type K thermocouples. The specimen alignment and temperature profile were verified prior to testing. Figure 24 shows the dimensions of the LCF broach specimen used for In718 which is identical to that used for titanium except for the length which was increased from 3.4 inches to 5.5 inches minimum to accommodate the heating element for the elevated temperature testing.

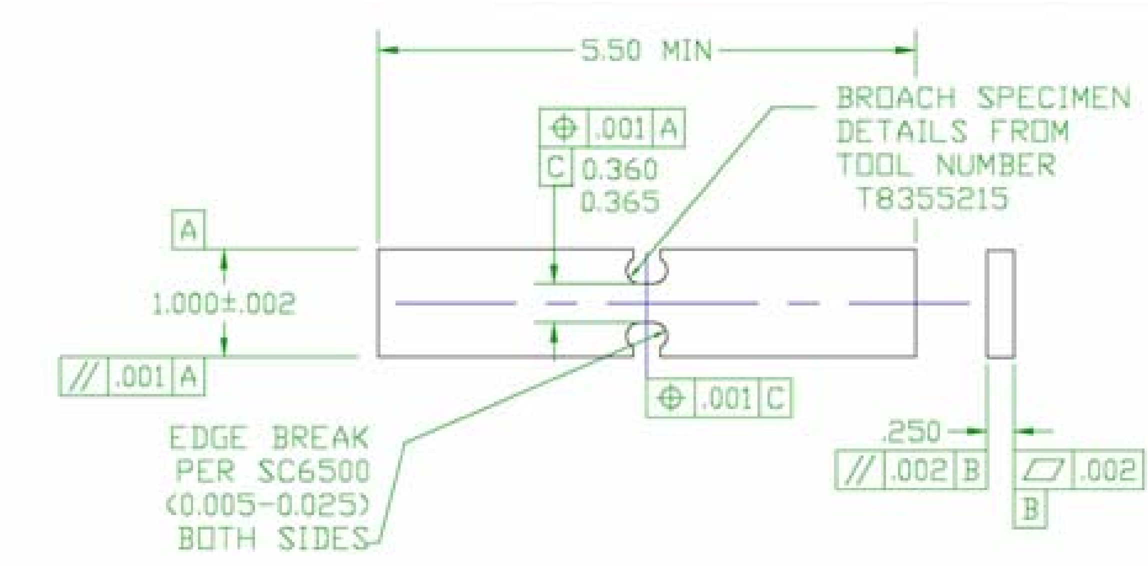


Figure 24. Low Cycle Fatigue specimen configuration.

Load controlled LCF testing was performed using the following test conditions:

- Sinusoidal loading cycle
- Test Temp = 1022°F (550 °C)
- Test Frequency = 5 Hz
- R ratio = 0.1
- Stress Range = 100 ksi

Test Blanks

“Short” sample blanks (60 blanks: 3.4” x 0.750” x 1.0”) were extracted from the In718 forging using the EDM process (See Figure 25). These samples were used for the designed experiments specimens, metallographic specimens, and NDE specimens. “Long” samples (12 blabks: 6.0” min x 0.750” x 1.0”) were extracted from the forging to be used as blanks for creating the elevated temperature fatigue (LCF) test specimens. The extended length was required to accommodate the heating equipment used for elevated temperature testing. Figure 3 shows the layout of the extracted sample blanks from the In718 pancake forging.

After broaching the deliverable LCF sample blanks, the EDM process was used to extract the 0.250” thick LCF specimens shown in Figure 24. Surface grinding was used to achieve the critical dimensions (flatness and parallelism) required for LCF specimens. An edge break operation was used in the broached gage section to reduce the risk of flaw initiation at the sharp transition between the specimen sides and the broached surface.

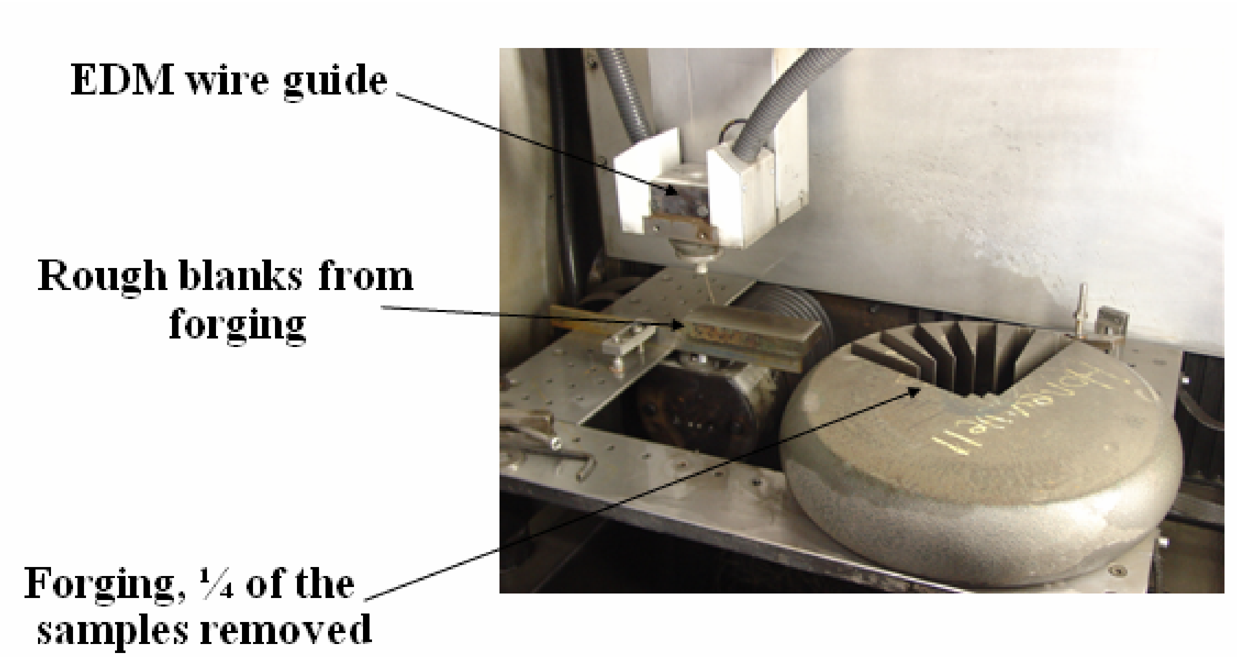


Figure 25. The EDM setup used for extracting the In718 coupons for the broaching samples from the 14 inch diameter 3.5 inch thick In718 pancake.

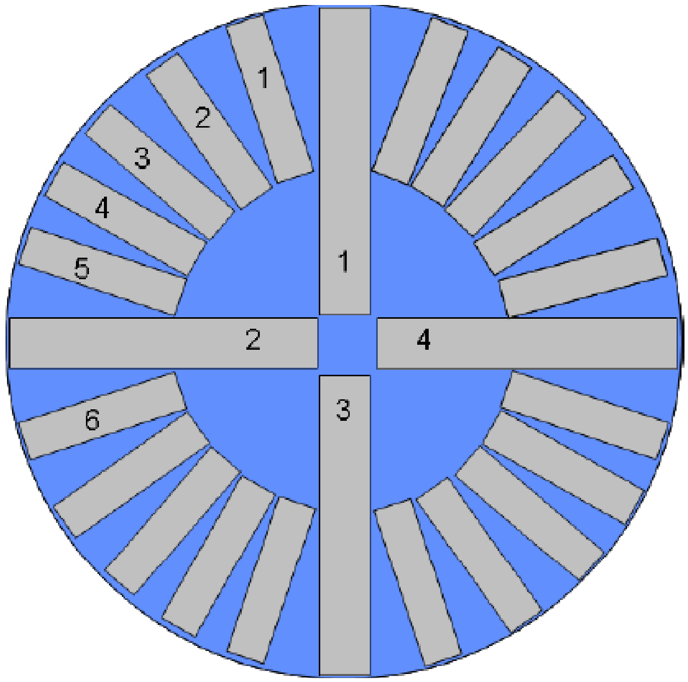


Figure 26. The layout of the extracted sample blanks from the In718 pancake forging. “Short” sample blanks (60 blanks: 3.4” x 0.750” x 1.0”) were used for NDT and Metallography. “Long” samples (12 blanks: 6.0” min x 0.750” x 1.0”) were using for LCF fatigue testing at elevated temperature.

Broach Geometry and Terminology

Figure 27 shows the profile of the broached slot. Figure 28 shows the “crown” area and the “pressure angle” area. The pressure angle serves as the contact surface for inserted blades.

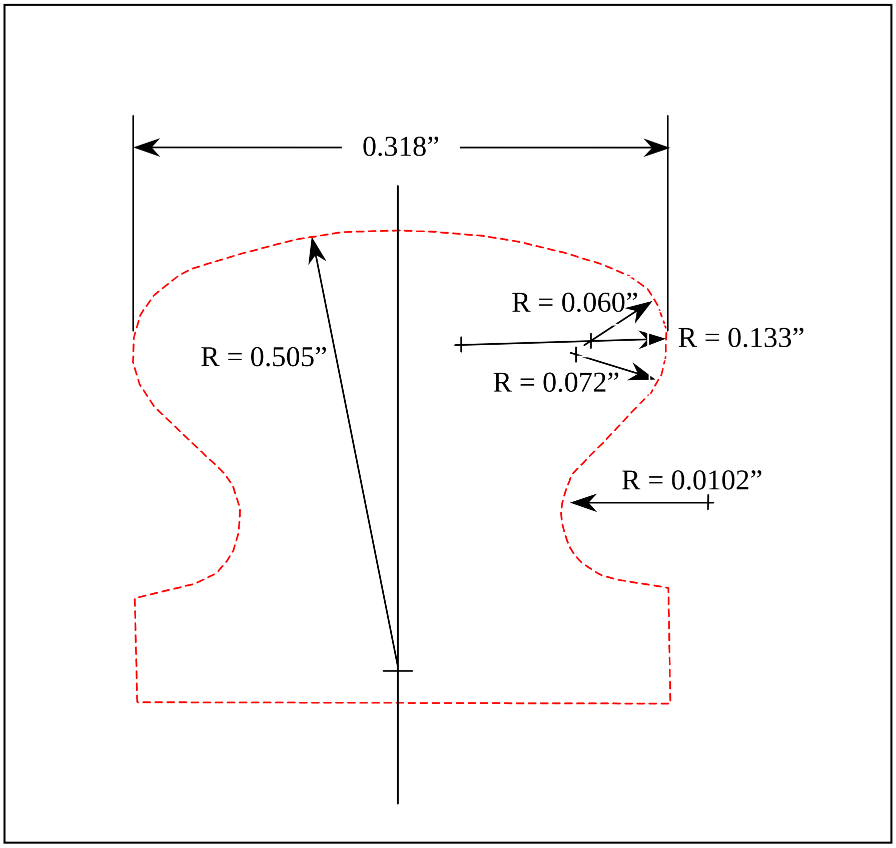


Figure 27. Broach profile dimensions for In718 specimens.

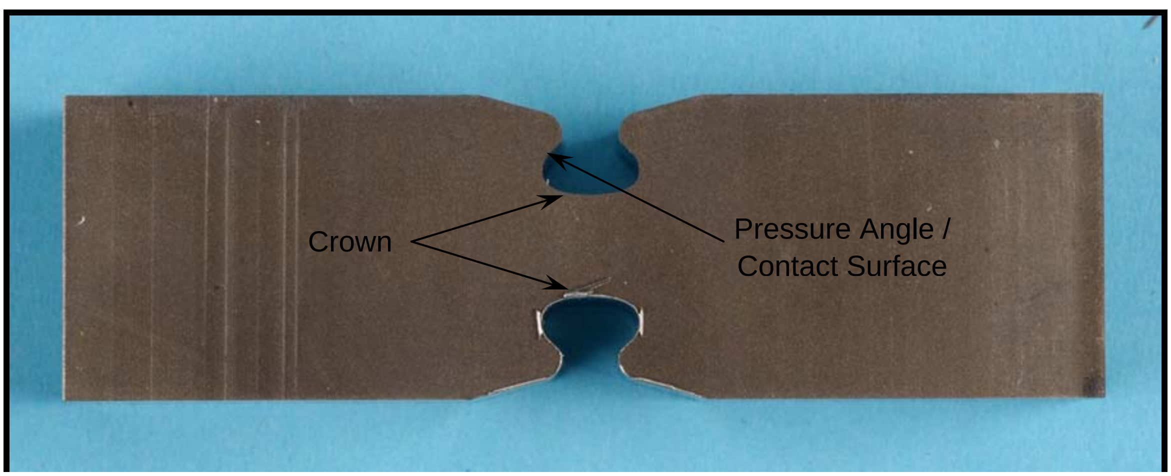


Figure 28. Broach profile nomenclature.

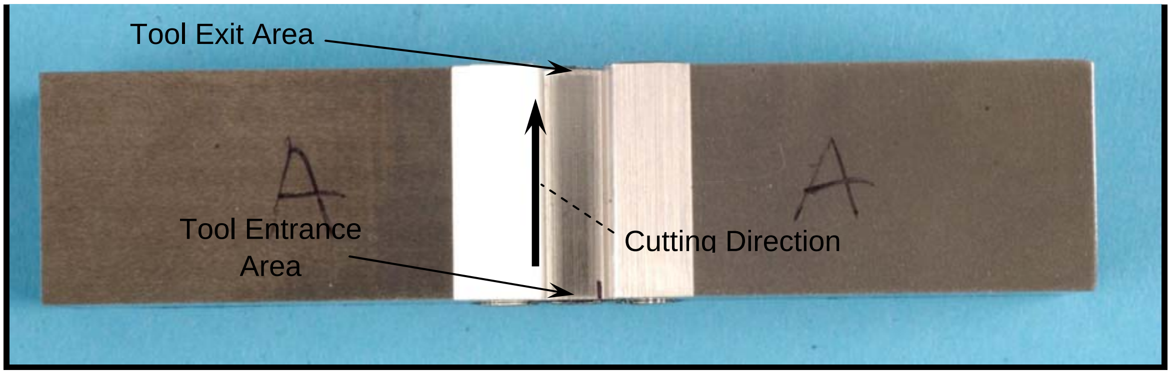


Figure 28 (continued). Broach profile nomenclature.

The Broaching Process

The broach slot is created by a series of tools that have teeth which remove small amounts of material from the broach slot. A typical broach slot is the result of the cutting action of several hundred individual teeth that are pulled through the sample. Each individual cutter tool is designed to remove material from one area of the slot. The cutter tools work together as a group to create the complete broach slot profile. The first group of tools is typically referred to as "roughers", and they remove relatively large amounts of material with each tooth. The final sets of cutters take a less aggressive cut and bring the broach slot to the final dimensions. In certain cases a single carbide insert that contains the complete broach slot profile is used to ensure tight dimensional tolerances. Figure 29 shows a picture of a final crown cutter tool and Figure 30 is a picture of the carbide insert form cutter.

The baseline "pristine" samples were broached using typical production conditions and settings as follows:

- Cutting Speed: 5 ft/min
- Coolant: ON
- Crown Cutter cutting edge: Sharp
- Carbide Form Cutter edge: Sharp
- Tool offset: None

Figure 31 shows a typical surface of a pristine sample broached using the above parameters and Figure 32 shows the resulting typical microstructure of a pristine sample in In718.

Figure 29. Typical Crown Cutter Tool.

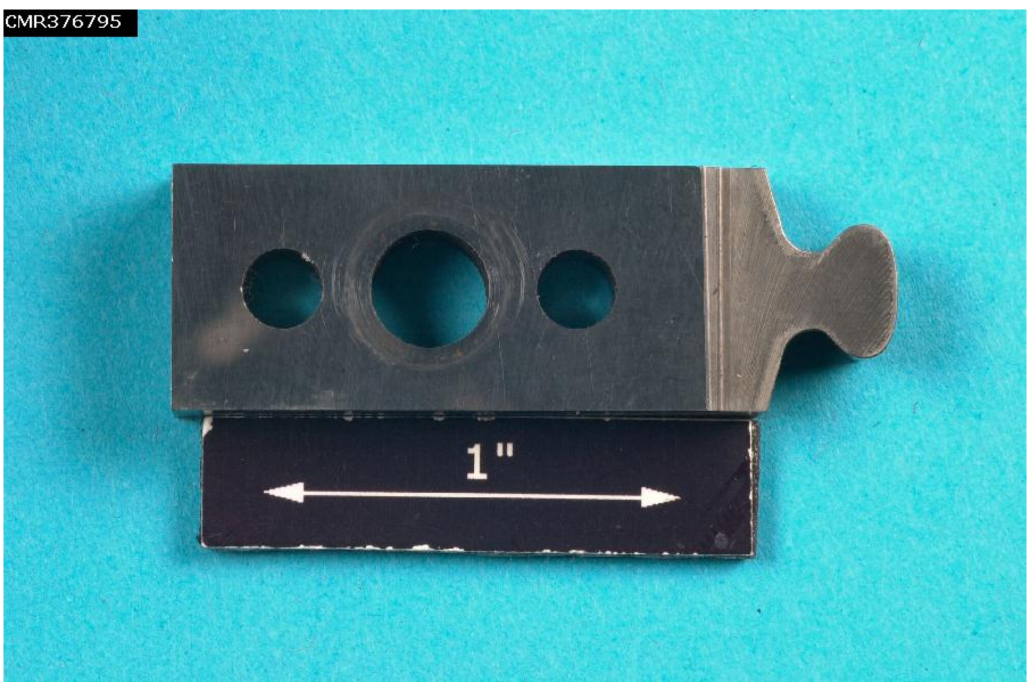


Figure 30. Carbide Insert Form Cutter.

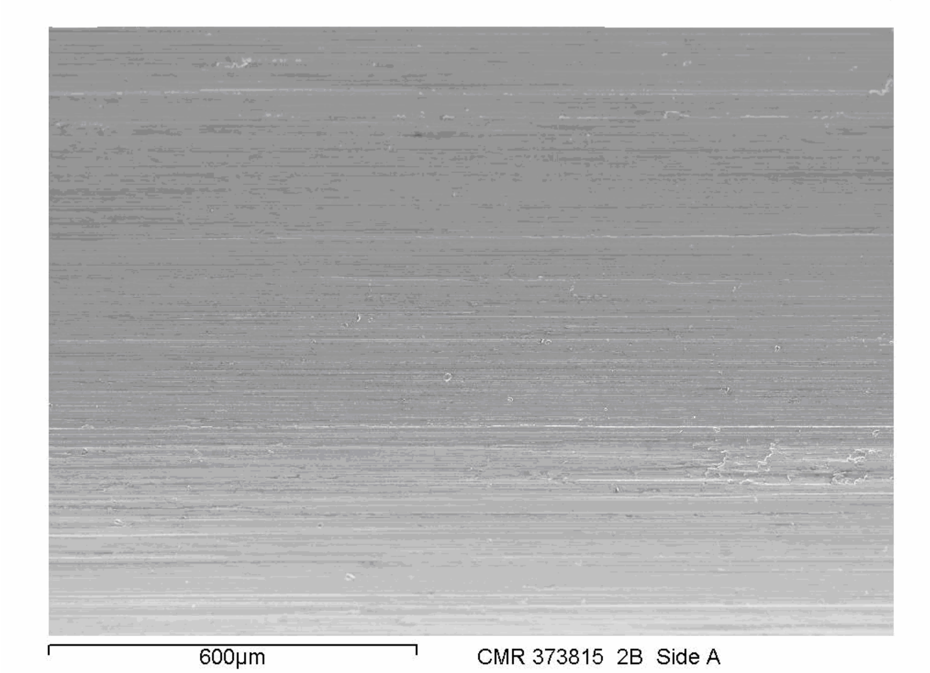


Figure 31. A typical surface of a pristine sample broached using typical broaching parameters of 5ft/min, coolant on, sharp tool, no offsets (100X).

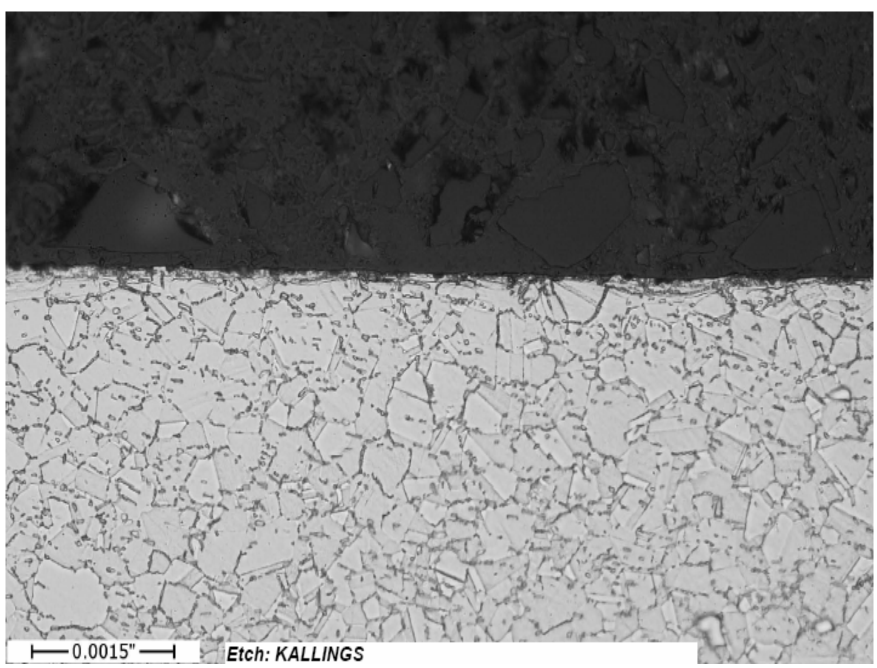


Figure 32. The resulting typical microstructure of a pristine broached sample in In718 (500X).

Fabrication of Type 1 Anomalies in In718 with Broach Processes

The "Type 1" amorphous layer anomaly was consistently produced with the broaching process in the In718 samples at production cutting speeds. A dull crown cutter tool and a significant offset of the crown cutter tool in the positive direction were required to make the defect.

Although the maximum depth of damage was produced with the coolant off, an amorphous layer was also produced with the coolant on and at even lower cutting speeds on development test specimens.

The thickness of the amorphous layer was typically larger near to the tool entrance and the damaged layer became thinner towards the tool exit region. Figure 33 shows a typical surface resulting during the broaching of this type of anomaly. The broach conditions used were:

- Cutting Speed: 5 ft/min
- Coolant: Off
- Crown Cutter cutting edge dulled (last of the tools)
- Crown Cutter offset 0.015" in the "positive" direction
- Carbide Insert form cutter removed

Figure 34 and Figure 35 show Type 1 damage in region near to the tool entrance. The amorphous layer was measured at ~ 0.0007" deep and grain distortion was observed to depths of ~ 0.0025". Figure 36 shows the amorphous layer near the tool exit region of the broach slot. The amorphous layer was measured at ~ 0.0005" deep with grain distortion to a shallower depth of ~ 0.0015".

In addition to the Type 1 defect observed across the length of the broached slots, limited areas of voiding were observed in the amorphous layer. Figure 37 is typical of the voids observed in these samples.

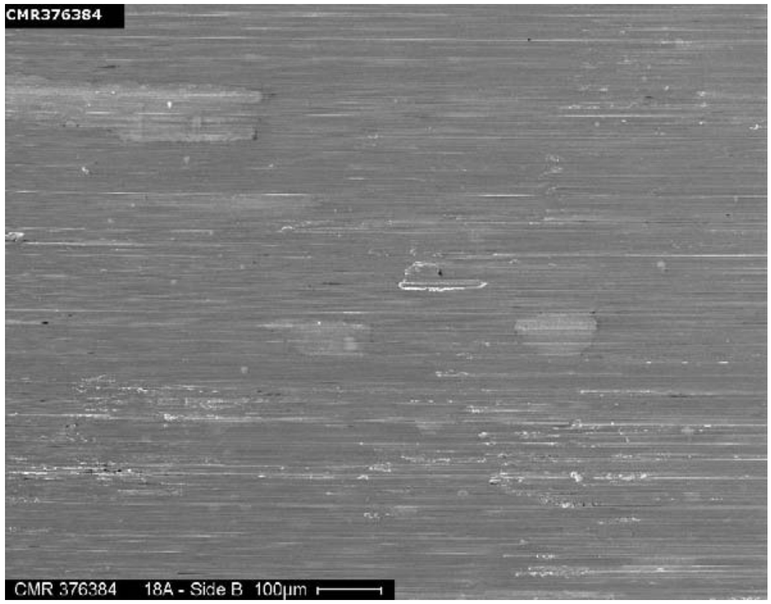


Figure 33. A typical surface of a broached sample with Type 1 anomaly (amorphous layer, 100X).

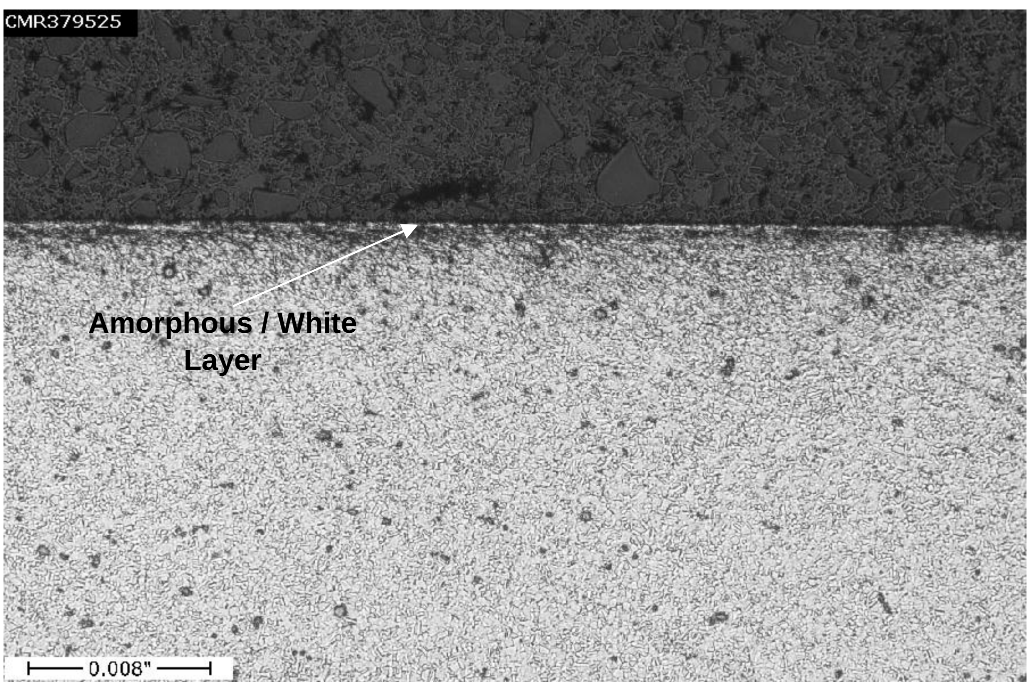


Figure 34. Amorphous layer observed near the tool entrance. Cross section through crown line (100X, Etch – Kallings).

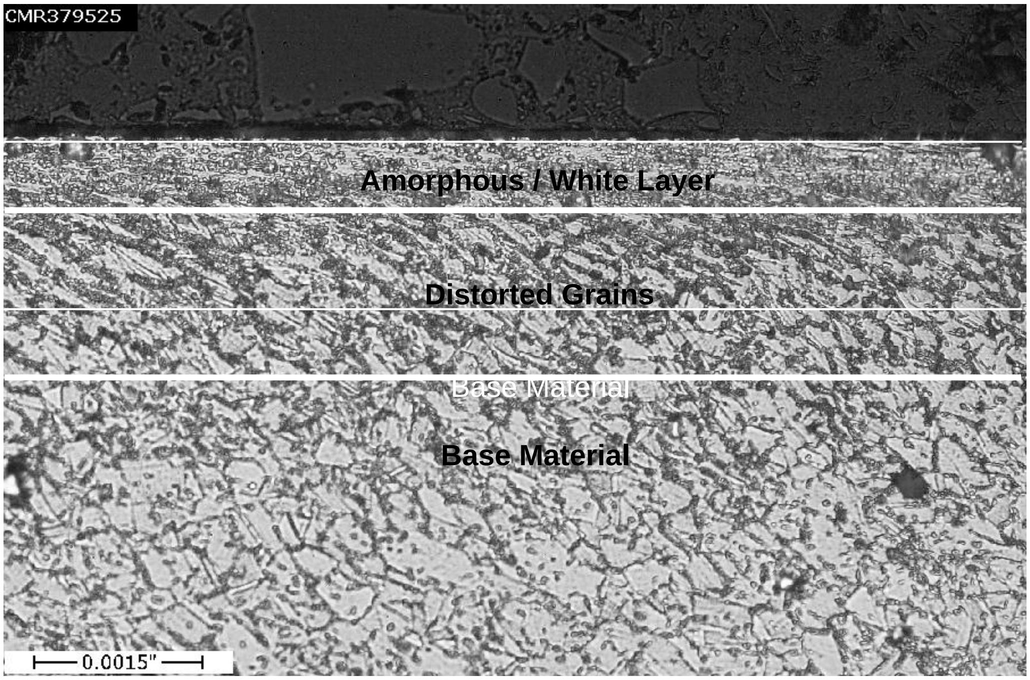


Figure 35. Amorphous layer observed near the tool entrance. Cross section through crown line (500X, Etch – Kallings).

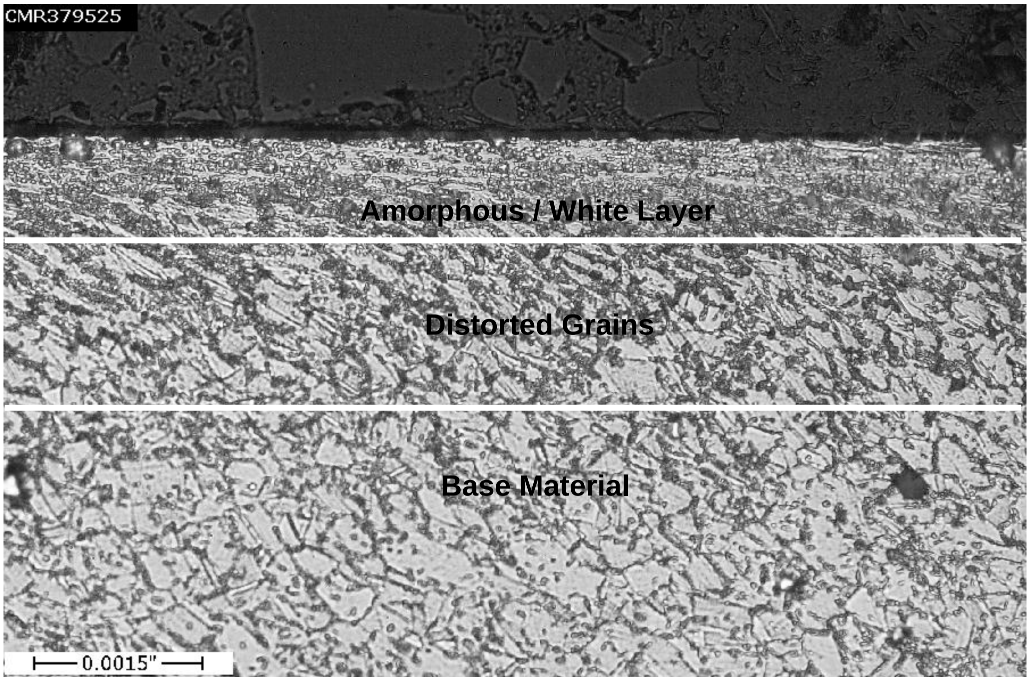


Figure 36. Amorphous layer observed near the tool exit. Cross section through crown line (500X, Etch – Kallings).

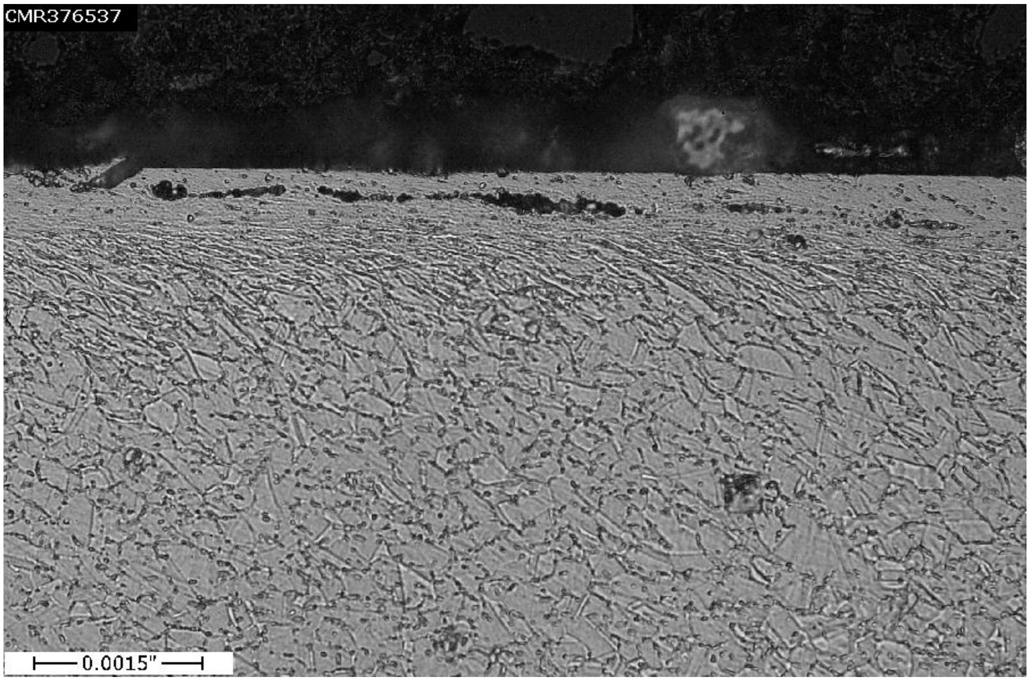


Figure 37. Voids observed in amorphous layer in broached slot mid-section. Cross section through crown line (500X, Etch – Kallings).

Methods Used for Control/Replication

The same broaching parameters listed previously were used for all of the deliverable samples. Metallurgical sections were taken from samples made at the start and end of the broaching campaign to confirm that there was no excessive drift in the process. The same broach tool set and broach machine were used for the sample fabrication.

<u>Fabrication of Type 6 Anomalies in In718 with Broach Processes</u>

The "Type 6" anomaly was produced with the broaching process in the In718 samples at production cutting speeds by offsetting the carbide insert form cutter in the positive direction. The coolant was turned on to minimize the amount of metallurgical damage to the substrate due to overheating.

The Type 6 anomaly was only observed near the exit region of the broach slot on the "pressure angle" (i.e. contact surface). Metallurgical sections were taken in the longitudinal direction through the defect on the broach contact surface. Figure 38 is a low magnification image of the re-deposited material near the tool exit region of the broached slot. Figure 39 is a higher magnification image of the re-deposited material area on the surface. It can be seen that the re-deposited material appears to be both discontinuous and continuous with the surface depending upon the location. When evaluated with optical microscopy, the re-deposited material is metallurgically similar in appearance to the amorphous layer observed in the Type 1 anomaly samples.

In the sectioning plane used to evaluate the Type 6 anomaly, the substrate below the re-deposited surface exhibits very little damage with some limited areas of grain distortion. Away from the re-deposited material toward the tool entrance, there is no re-deposited material and very little damage to the substrate.

Figure 40 and Figure 41 are SEM images at 10X and 40X of the defect produced. It is very clear from the metallographic cross sections and the SEM images that the anomaly produced contains a geometric component and can not be described as strictly a Type 6 defect. The defect produced on these samples contains characteristics that are common to Type 8 (i.e. Laps) anomalies. The re-deposited material can be visually detected with the unaided eye due to the geometric component and the macroscopic scale of the anomaly.

In addition to the Type 6 anomaly on the broach slot contact surface, a limited amount of the Type 1 anomaly was observed in longitudinal metallurgical sections taken through the center of the broach slot crown. Figure 42 shows the grain distortion that was present in the samples near the tool entrance. Grain distortion makes up the majority of the damage, with little amorphous layer observed.

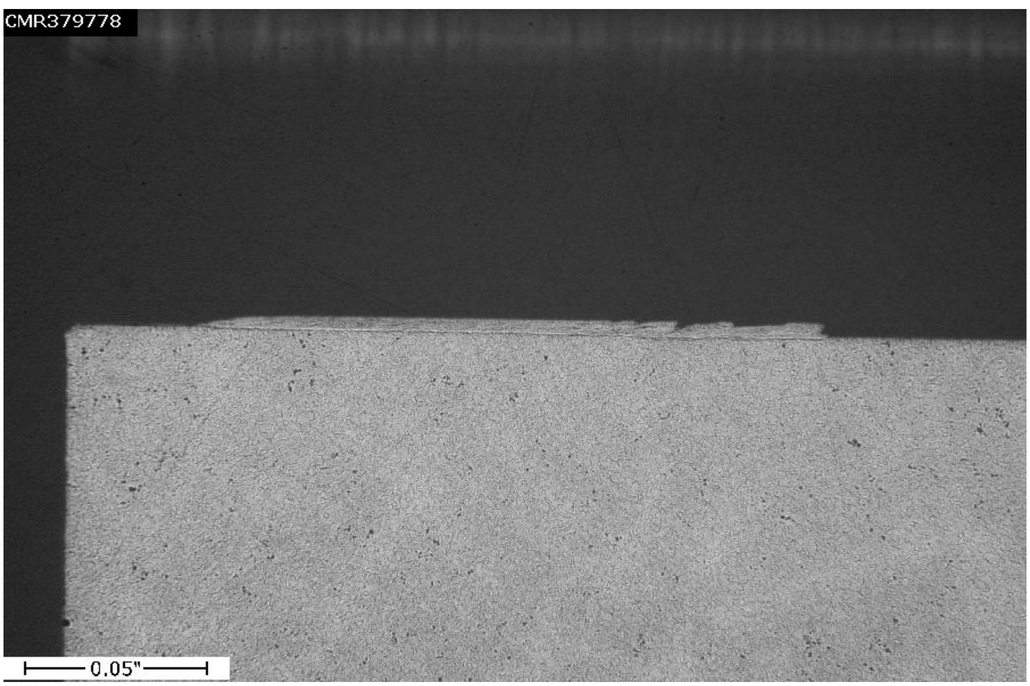


Figure 38. Re-deposited layer observed near the tool exit. The cross section was taken through pressure angle (16X, Etch-Kallings).

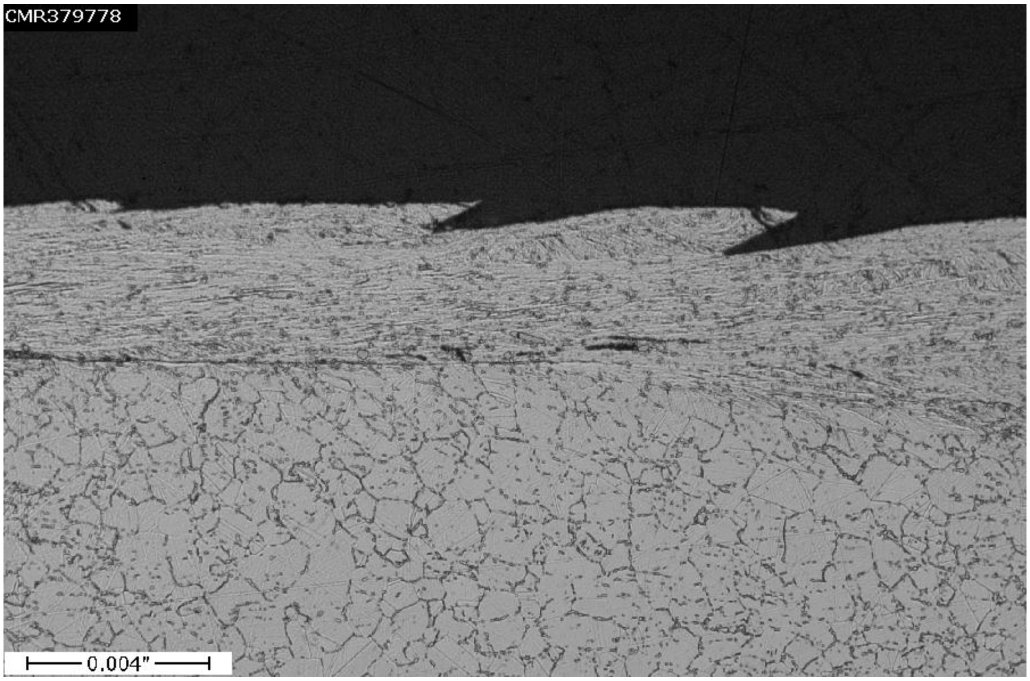


Figure 39. Re-deposited layer observed near the tool exit. The cross section was taken through pressure angle (200X, Etch-Kallings).

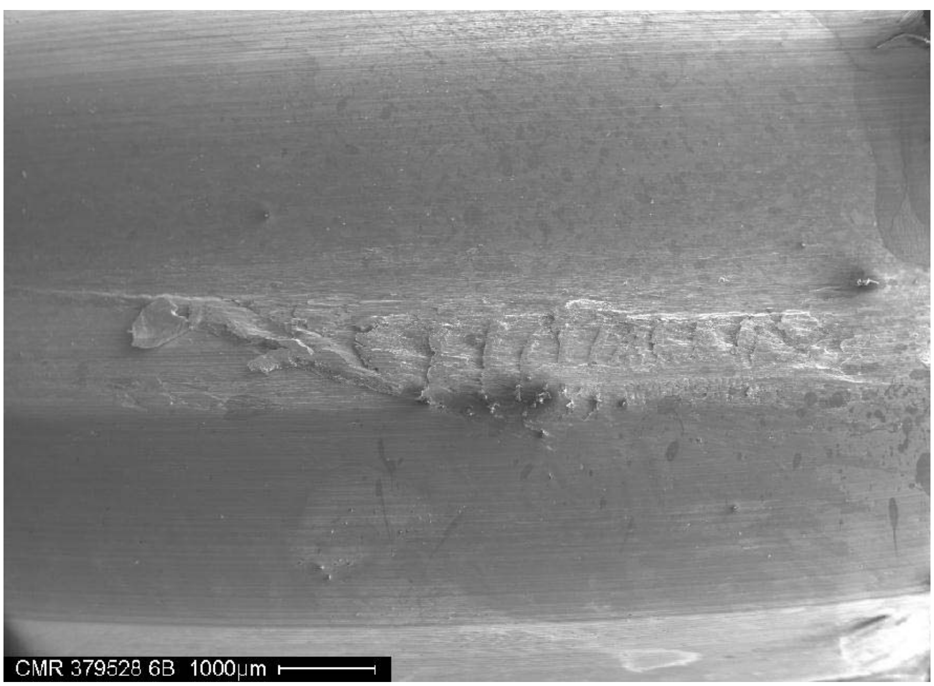


Figure 40. Re-deposited layer observed near the tool exit, pressure angle (10X).

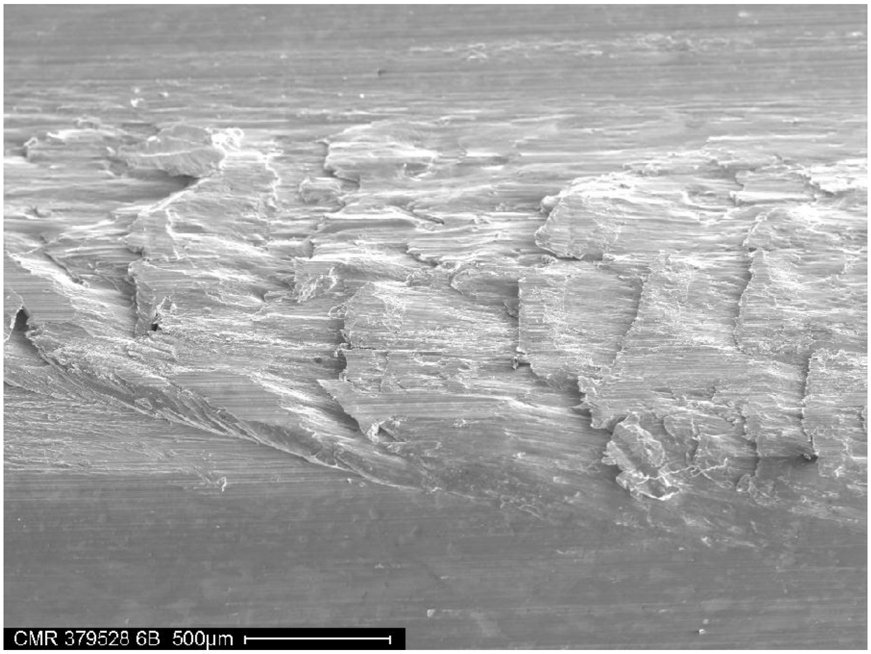


Figure 41. Re-deposited layer observed near the tool exit, pressure angle (40X).

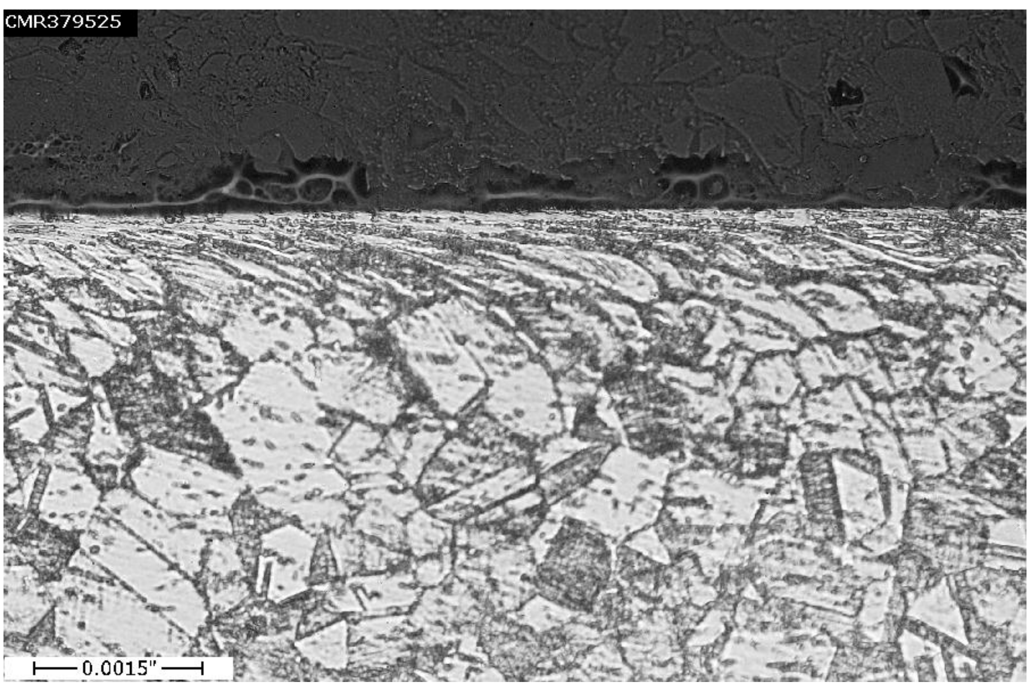


Figure 42. Type 1 anomaly observed near the tool entrance. The cross section was taken through the crown line (500X, Etch-Kallings).

The broaching parameters used to produce the smearing (Type 6) anomaly in In718 were:

- Cutting Speed: 5 ft/min
- Coolant: On
- Crown Cutter cutting edge dulled
- Crown Cutter offset 0.007" in the "positive" direction
- Carbide Insert form cutter dulled and in place (last of the tools)
- Carbide Insert offset 0.015"

LCF Results Anomalies in In718 With Broach Making Processes

Table 8 summarizes the results from the LCF testing for all conditions. Note that only two specimens of each condition were used in generating LCF results. This number of samples is not enough to capture the scatter in LCF results and therefore the results should be viewed as very preliminary and more qualitative than quantitative. The results shown in Table 8 are graphically plotted in Figure 43 along with the average fatigue life deficit expected for the two anomaly conditions under consideration.

In should be mentioned here that the failure initiation site in the samples with the Type 6 anomaly is well away from the anomaly. The location of the anomaly is in a low stress region and therefore does not impact the life of the test specimen. The reduction in life observed is likely due to some other anomaly present in the gage section.

Table 8. Low Cycle Fatigue (LCF) testing results for In718 samples with and without broaching anomalies.

Specimen Condition	Specimen ID	Cycles to failure (N_f)
Good specimen	1C-2	388,486
	2B-2	113,294
Smeared defect	1A-A	61,460
	3A-A	139,289
Amorphous Layer	4C-B	125,728
	3C-B	145,217

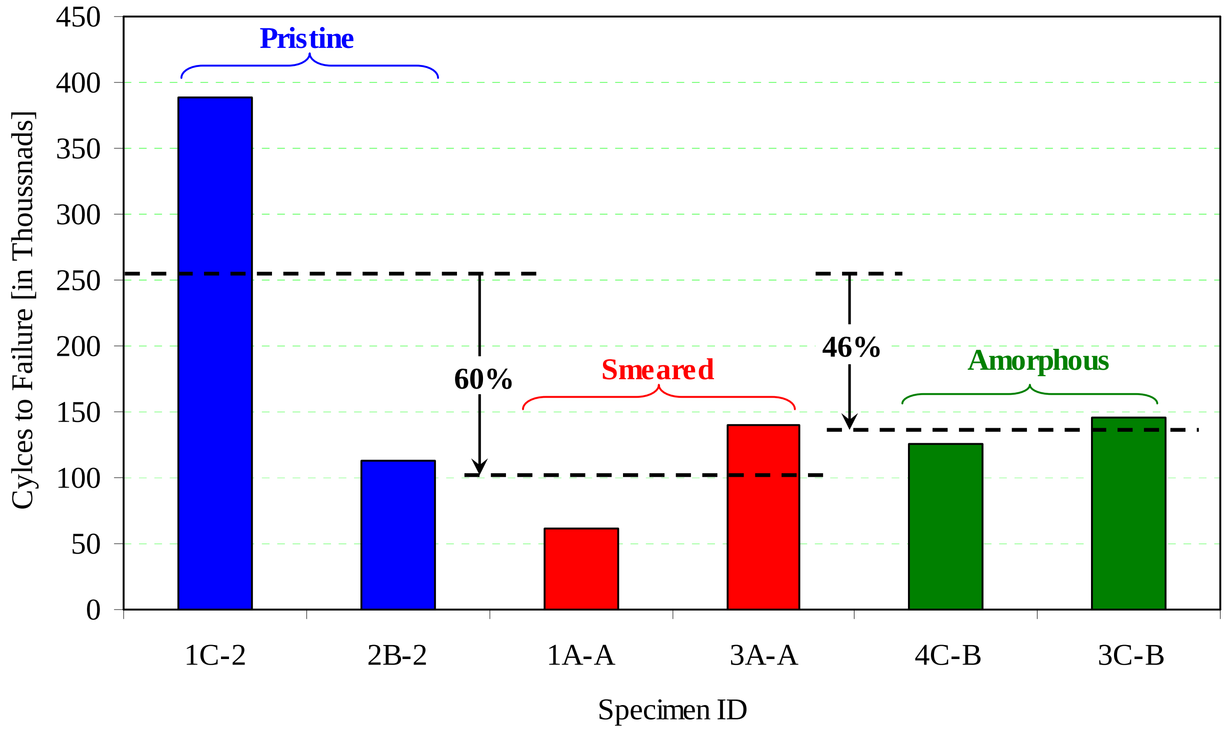


Figure 43. Comparison of the LCF testing results for pristine broached samples, broached samples with smeared anomaly, and broached samples with amorphous layer anomaly in In718.

From the results shown in Table 8 and Figure 43, it is estimated that on the average there is about 60% reduction in the low cycle fatigue life of the broached specimens containing the smeared anomaly (although the failure was not caused by this anomaly) and about 46% reduction in the low cycle fatigue life due to the amorphous layer anomaly. Again the reader is cautioned not to use these values in any quantitative analysis related to component life assessment but to use these values as a qualitative guide of the effect of such anomalies on the LCF life.

Summary In718 Broach Making Processes

Type 1 anomalies in In718 material were readily manufactured by offsetting dull tooling and cutting with no coolant flow. An amorphous/white layer was formed in the layer nearest to the cutting surface, and distorted grains were formed below the white layer. The machining of the Type 1 anomaly is considered repeatable and relatively controllable.

Type 6 anomalies in In718 material were manufactured by offsetting a dull carbide insert form cutter and cutting with coolant flowing. The re-deposited material was created on the contact surface of the broach slot near to the tool exit region. There was limited damage to the substrate below the re-deposited material. Although multiple samples with Type 6 anomalies were manufactured and the anomaly was subsequently reproduced on the deliverable samples, the mechanism responsible for creating the Type 6 defect is not well understood.

Subtask 2.3 – Preliminary Evaluation Matrix and Initial Results:

The initial effort of this subtask is to define a metric that represents how well each inspection technology is able to detect the eleven types of flaws. A generic protocol will be developed to compare the various techniques using a weighting scheme such as a low, medium, and high for identified factors. Effort under this activity has been delayed until the test samples for Option A become available for use.

Subtask 2.4 – Specimen testing:

Using the test specimens obtained in Subtask 2.1 data will be generated to (1) further evaluate the capability or (2) validate the stated (assumed) capability of the advanced NDE techniques selected in Subtask 2.3 to detect the eleven anomaly types. Effort under this activity has been delayed until the test samples for Option A become available for use.

Subtask 2.5 – Data analysis:

The advanced NDE techniques identified in the preliminary evaluation subtask, 2.3, will be used in evaluating some subset of the specimens purchased in subtask 2.1. This evaluation will concentrate on preliminary determination of the NDE process capability using the test samples produced with real anomalies of known sizes. During this process critical inspection parameters will be identified. Effort under this activity has been delayed until the test samples for Option A become available for use.

Subtask 2.6 – Interim report:

A summary report of the work completed in subtask 2 will be provided in draft and final form per the SOW. It is expected that this document will be publishable as an FAA report either as a stand-alone document or for incorporation into the final project report. Effort under this activity has been delayed until the test samples for Option A become available for use.

NOTE: Tasks 3-5 are on hold pending release of program funding. All activity on these subtask elements was halted Nov 2005.

Task 3: NDE Process Development and Enhancement

Subtask 3.1 – NDE Process Development Plan:

Based on results of Task 2, promising techniques and/or methods will be selected for further development. The ETC team will develop a technical plan for consideration by the FAA, which shall include a description of the development and engineering necessary to improve the detection capability, reliability and productivity of each approach that is selected. The NDE process development plan will be presented to the FAA for consideration prior to continuing with the subtasks that follow. Activity is on hold.

Subtask 3.2 – NDE Process Enhancements:

Upon approval from FAA, technologies selected in subtask 3.1 will be further optimized. Optimization may include the design and fabrication of new probes or sensors, improved fixturing, or modification to inspection scanning or protocols. Activity is on hold.

Subtask 3.3 – NDE Process Enhancement Evaluation:

Using a larger sample set, data collection and evaluation of the enhanced NDE techniques selected in the subtask 3.1 and enhanced in subtask 3.2 will be completed. Verification of anomalies will be accomplished by conducting low cycle fatigue and metallographic evaluations. Correlation of the NDE responses with the metallurgical features of the anomalies will be sought for use in the quantitative validation that will occur in Task 4. Activity is on hold.

Subtask 3.4 – NDE Process Enhancement Reporting:

Using the data generated in subtask 3.3, the results of subtasks 3.2 and 3.3 will be documented. The data format and content will be coordinated with members of the POD working group such that all necessary data for POD estimates are recorded. Activity is on hold.

Task 4: Quantitative Validation of Technique Performance

Subtask 4.1 – Quantification of Technique Performance

A matrix that fairly compares the capabilities of each of the NDE methods for a given defect type will be generated in Task 2 and re-evaluated with the results from Task 3. Issues related to implementation potential will be considered including productivity, portability, and cost. A POD working group will be established for this purpose. Activity is on hold.

Subtask 4.2 – Validation of Technique Performance

Because of the disparate nature of the defect types and the number of flaws available, consideration will be given to appropriate methods to estimate POD. A POD working group will be established to assist in sample design as applicable, to guide data acquisition and analysis, and to provide reliability/performance estimates. Activity is on hold.

Subtask 4.3 – Preliminary Process Descriptions for NDE Enhancements

Based on the results of the program, preliminary process descriptions will be generated. Details will be of sufficient quality to enable individual OEMs, including members of MANHIRP and others, to generate internal specifications as applicable to their product. Activity is on hold.

Task 5: Final Report

Subtask 5.1 – Final Reporting

Draft and final report that includes results and conclusions of Tasks 2 through 4 will be prepared in the required FAA format. Activity is on hold.

Plans for the Next Quarter:

MANHIRP Activities

- Continue to work toward legal and contract agreements between ETC and MANHIRP to purchase test samples.

ETC Test Sample Activities

See updated project schedule file for detail.

- Obtain sufficient quantity of Ti 6-4 and In718 material for turn and broach Option C test samples.
- Begin fabrication of Option C (Ti 6-4 and In718) test samples.
- Offer to review Option A results with MANHIRP members.

Other Activities

- Coordinate NDE testing to allow OEMs and vendors the opportunity to examine the “Option A test samples” and allow them to update cost and schedule quotes and develop any necessary fixturing.
- Begin to identify and rank the elements of the “Evaluation Matrix” as NDE results are obtained.

Deliverables List

Description	Delivery Date	Status
Deliverable 1.1.a: A detailed project plan will be delivered within 30 days of completion of the subcontracting process with the OEMs. This plan will include a Gantt chart generated by Microsoft Project depicting tasks, milestones, and critical path. The project plan will be prepared and delivered via email and/or CD-ROM.	November 2004	11/04 – First generation plan delivered to FAA. Update planned upon completion of MANHIRP sample plan.
Deliverable 1.1.b: An initial project review will be conducted at a mutually agreed upon location. Notification of the dates and logistics of the meeting will be communicated to the FAA project monitor within five days of establishment of the subcontracts with the OEMs.	December 2004	12/04 – Meeting held December 3 -4, 2004 in Washington DC. Deliverable complete.
Deliverable 2.1: Deliver the remaining specimens from three (3) complete sets of test specimens containing the eleven (11) machining induced anomalies identified in the MANHIRP report at the close of the program. At least twenty (20) of each anomaly type will be delivered. Provide results of test specimen characterization and comparisons. Descriptions of the processes used to generate each defect type will be included in the report delivered as part of Subtask 2.6.	In progress under Option A. Pending FAA review of ETC progress with test sample fabrication capability.	6/05 - A signed nondisclosure agreement between ETC and MANHIRP is verbally approved by all parties. Final signature approval is expected in July 2005. First teleconference between MANHIRP and ETC is scheduled after the NDA is signed. After which purchase orders can be placed for procurement of the test samples. 6/06 – NDA has been signed by all parties and returned to Rolls Royce for distribution.
Deliverable 2.2: Deliver literature survey suitable for publication as an FAA document.	November 2005	Review of abstracts complete. A draft report created and submitted to FAA for review.
Deliverable 2.3.a: Develop and deliver an NDE evaluation matrix covering activity of Subtasks 2.1, 2.2 and 2.3.	TBD In progress under Option A	11/05 - Effort on this task has been limited to identifying NDE methods and or techniques identified through the *Literature Survey* and developing a scoring/ranking method.
Deliverable 2.3.b: Conduct a program review with the FAA that summarizes the results of the NDE evaluation matrix. The review will be held at a mutually acceptable location with the TFP, PF, and FAA representatives identified by the FAA project monitor. The FAA will review the recommendations and the	TBD Planned FAA review to be held November 2006. FAA to provide	3/06 - ETC is performing under a risk management (limited test sample fabrication plan - Option A) to determine if ETC can fabricate comparable test samples to that published in the public domain under the MANHIRP program. Test samples will be

Description	Delivery Date	Status
FAA project monitor will notify the PF and TFP in writing which NDE technologies are selected for continued activity under Task 3. For the review a detailed subtask project plan will be prepared. The subtask project plan will include a Microsoft Project file. The subtask project plan will reflect the objectives of all activity necessary to complete Subtasks 2.4, 2.5 and 2.6 and Task 3. Milestones and deliverables will be included within this subtask project plan. Task 3 will not be initiated until after the Subtask 2.3 project is reviewed and approved by the FAA project monitor. Subsequent changes to the original project plan and the subtask project plan, which are identified during the review process, will be submitted to the FAA project monitor at the first monthly reporting. Upon approval of the Subtask 2.3 project plan, detailed cost estimates will be provided for Task 3.	decision for final MANHIRP vs. ETC fabrication of test samples. Elements of this subtask will be discussed.	compared through metallography characteristics and low cycle fatigue debit analysis. 12/06 – Option A samples completed and analyzed for Ti-6-4. Report submitted to FAA November 2006 summarizing results.
Deliverable 2.5: Review and present the results of Subtasks 2.2 through 2.5 and provided final recommendations of NDE candidates for Task 3. A representative of the AANC shall also attend this review. The FAA will review the recommendations and the FAA project monitor will notify the PF and the TFP in writing which NDE technologies are selected for Task 3 within 10 business days after the brief. Task 3 shall proceed upon receipt of the FAA project monitor approval letter.	TBD	
Deliverable 2.6: Prepare and deliver a Task 2 final report in FAA format.	TBD	
Deliverable 3.1.a:A technical plan for enhancing the performance of the NDE techniques specified by the FAA from the results of Subtask 2.4	TBD	On hold per FAA contractual direction.
Deliverable 3.1.b: A review meeting will be conducted to evaluate the technical plan and provide final recommendations of specific NDE performance enhancement candidates. The FAA will review the technical plan recommendations and the FAA project monitor will notify the PF and the TFP in writing of any changes to the plan. The FAA project monitor will provide this approval in writing within 10 business days after the briefing. Task 3.2 shall not proceed prior to receipt of the FAA	TBD	On hold per FAA contractual direction.

Description	Delivery Date	Status
project monitor approval letter.		
Deliverable 3.4.a: Deliver all test specimens upon completion of subtask 3.4 testing.	TBD	On hold per FAA contractual direction.
Deliverable 3.4.b: Summary evaluation report of task 3 results and recommendations.	TBD	On hold per FAA contractual direction.
Deliverable 4.2: Summary of POD approach and POD curves including all data used to generate the POD curves.	TBD	On hold per FAA contractual direction.
Deliverable 5.1: Draft final and final report including initial NDE technique evaluation and selection, a description of various defects studied, NDE technique development and optimization results, assessment of production readiness, and POD approach/results.	TBD	On hold per FAA contractual direction.

Key milestones

Task Description	Original Date	Revised Date	Status
Task 1: Project Planning			
Submit detailed MS Project plan and review in meeting with FAA	November 2004	Complete	11/04 – First generation plan delivered to FAA. Update planned upon completion of MANHIRP sample plan.
Task 2: NDE Technique Evaluation and Selection	*3 – 24*		
Finalize sample descriptions and establish SOW with MANHIRP members.	Jan 05	Jun 06	6/05 – NDA has been established with MANHIRP. Technical discussions began Jul 05.
Initiate sample fabrication with MANHIRP.	Feb 05	Complete	1/05 – Initial technical discussion held with MANHIRP members
Determine if successful progress is being made on sample fabrication. Initiate OEM fabrication (Option 2 – O2) if necessary.	May 05	May 05	6/05 – Options were reviewed with FAA in Apr 05. Decision made to proceed with MANHIRP discussions and purchase of samples.
Complete MANHIRP sample fabrication.	Sep 05	Pending	6/05 - Draft P.O. generated awaiting MANHIRP

Task Description	Original Date	Revised Date	Status
			authorization for purchase orders through RR.
Complete OEM sample fabrication if option was exercised.	Dec 05	N/A	6/05 - OEM option was not exercised – Options were reviewed with FAA in Apr 05. Decision made to proceed with MANHIRP discussions and purchase of samples. 11/05 – ETC/FAA revisited OEM option. Detailed plan to be discussed at ROMAN annual meeting. 2/06 – FAA selected OEM sample fabrication plan, “Option A”.
Sample characterization from MANHIRP option.	Dec 05	Aug 06	6/05 - Awaiting MANHIRP authorization for purchase orders through RR.
Sample characterization from OEM option.	Feb 06	N/A	6/05 - OEM option was not exercised – Options were reviewed with FAA in Apr 05. Decision made to proceed with MANHIRP discussions and purchase of samples.
Initiate literature survey	Dec 04	Complete	4/05 – Literature survey initiated 6/06 – ETC samples from Option A to be characterized in Fall, 2006.
Identify any additional technologies from results of literature survey and seek concurrence from FAA to include in NDE evaluation matrix.	July 05	Complete	Review of abstracts completed Sept. 05 Review meeting held with the FAA Nov. 05.
Complete literature survey and submit draft version to FAA.	Aug 05	Complete	Final draft sent for FAA review Dec. 05.
Finalize literature survey per FAA comments.	Oct 05	Dec. 05	Pending FAA review.
Finalize comparison matrix and review in meeting with FAA.	May 05	Complete	Review meeting held with the FAA Nov. 05.
Establish purchase orders with subcontractors that will participate in preliminary evaluation studies.	Apr 05	MANHIRP TBD Option A June 06	11/05 – Draft P.O. generated awaiting MANHIRP authorization for purchase orders through RR.
Initiate preliminary evaluation at ETC member organizations and at subcontractors. Initiation date will be moved earlier as specimens become available.	Dec 05	MANHIRP TBD Option A Aug. 06	
Complete preliminary evaluation.	Jul 06	MANHIRP	6/06 - Option A (draft) evaluation matrix

Task Description	**Original Date**	**Revised Date**	**Status**
		TBD Option A Nov. 06	elements will be reviewed with the FAA during the meeting to establish final selection of test sample (ETC or MANHIRP)
Complete evaluation matrix.	Oct 06	TBD	
Sample characterization including limited fatigue tests with FAA concurrence of testing plan.	Nov 06	TBD	
Complete data analysis of preliminary evaluation and document results in interim report. Interim report will be written such that it is easily incorporated into the final project report. Complete FAA review of Task 2 results such that Task 3 can be initiated.	Jan 07	TBD	
Task 3: NDE Process Evaluation and Development		TBD	On hold per FAA contractual direction.
Complete NDE process development plan and review with FAA for concurrence.	25	TBD	On hold per FAA contractual direction.
Initiate NDE process development and enhancement studies and assess improvement against baseline established in preliminary evaluation.	26	TBD	On hold per FAA contractual direction.
Complete NDE process enhancements.	32	TBD	On hold per FAA contractual direction.
Complete NDE process enhancement assessment using a full sample set including data acquisition/tabulation for use in POD assessment.	32 – 36	TBD	On hold per FAA contractual direction.
Document NDE process enhancement results.	37 – 39	TBD	On hold per FAA contractual direction.
Task 4: Quantitative Validation of Technique Performance	*15 – 36*	TBD	On hold per FAA contractual direction.
Initiate planning for POD studies which takes into account disparate nature of the inspection methods. Provide input into data format to ensure later usability for POD assessment.	8	TBD	On hold per FAA contractual direction.
Complete POD protocol for use by NDE process development team to guide data acquisition and documentation.	26	TBD	On hold per FAA contractual direction.
Provide coordination with task 3 team members as necessary during NDE process enhancement studies.	27 – 36	TBD	On hold per FAA contractual direction.
Complete data analysis to validate technique performance.	36 – 40	TBD	On hold per FAA contractual direction.

Task Description	Original Date	Revised Date	Status
Generate preliminary process descriptions for NDE enhancements.	30 – 40	TBD	On hold per FAA contractual direction.
Task 5: Final Demonstration and Reporting	*36 – 42*	TBD	On hold per FAA contractual direction.
Initiate final documentation.	36	TBD	On hold per FAA contractual direction.
Submit draft final report.	41	TBD	On hold per FAA contractual direction.
Submit final report.	42	TBD	On hold per FAA contractual direction.

Risk Assessment

The following risk items and applicable mitigation plans have been identified:

Entry Date	Risk Item	Impact	Mitigation Plan	Status	Closure Date
Apr 2004	Difficulties with establishing purchase order with foreign suppliers and/or ability of one or more of the MANHIRP members to deliver samples in a timely manner.	Program is dependent on sample availability.	OEMs have established internal capabilities for use as necessary.	6/05 – OEMs reviewed internal capabilities to generate samples including cost and schedule information for use if necessary. Current agreement with FAA is to continue with MANHIRP process give mutual benefits of program cooperation.	
April 2004	To comply with overall period of performance constraint of 42 months, multiple technologies must be evaluated in parallel. Concern exists with having similar samples which can be evaluated by different techniques.	SOW states that 2 sets of specimens (20 specimens for 11 defect types) for a total 440 specimens should be fabricated. Some samples will be destructively characterized but a sufficient number are needed for use in final POD assessment. Samples for POD need more thorough characterization such that curves can be generated.	Given schedule compliance issues and need for POD set, ETC recommends that an additional set of 220 specimens, for a total of 3 sets, be included in the program.	6/05 – ETC understanding of sample configurations improved through additional discussion with MANHIRP with further enhancements expected. As ETC proceeds with sample fabrication decisions, consideration will be given for evaluation and POD requirements.	

Entry Date	Risk Item	Impact	Mitigation Plan	Status	Closure Date
April 2004	Some technologies may be identified during the literature survey. Given that the SOW process has been initiated with known suppliers as part of the proposal process, activity of those identified in the literature survey will lag behind to some extent.	Potential delay in generation of comparative matrix.	Establish interest on the part of the subcontractor while FAA review of ETC recommendation is underway.		
April 2004	Subcontracts and coordinated research agreement	There could be a delay in start of the technical program while subcontracts and the coordinated research agreement are being put in place.	ETC members have agreed to begin discussion of the CRA prior to actual receipt of the award from FAA to ISU.	1/05 – Subcontracts were not in place until Dec 04 which lead to initial delays. The impact was minimal, compared to NDA issues.	Jan 2005 – All ETC agreements are in place.
March 2006	Delivery of samples from MANHIRP remaining a high risk item.	Program delay.	ETC members proposed “Option A” in which ETC members will prepare a limited sample set to determine feasibility of full ETC sample fabrication.	6/06 – Ti samples are underway. Materials identified for Ni samples. 12/06 – Ti samples complete Ni samples underway.	March 2007

Engine Titanium Consortium Phase III – Project I – AMD Team List

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Project 2: Thermal Acoustic Studies of Engine Disk Materials

Background

As with many aerospace applications, jet engine components are operated in demanding environments, often at extreme temperature and stress conditions. Given these demands, engine components are inspected prior to entering commercial service, typically using ultrasonics for subsurface, volumetric defects, and fluorescent penetrant inspection (FPI) for surface breaking defects. In special cases, other methods such as eddy current, radiography, or magnetic particle inspections may be used, as applicable. As the predominant surface inspection method, FPI requires a clean, dry part which is processed using the recommended process parameters for penetrant application, penetrant removal, developer application, and inspection[4]. Using these process parameters, laboratory 90/95 POD values have been demonstrated as low as 0.060" with 0.10" considered more typical[5]. FPI can be used to inspect the majority of part surfaces with restrictions including the need for reasonable line of site. While reliable FPI processes have been demonstrated, human factor effects can adversely affect the reliability, particularly in a production environment.

Given these limitations, additional methods that provide reliable surface defect detection in a cost effective manner, are needed. Early work on the beneficial effects of combining mechanical excitation with thermal detection to improve signal response was reported in the mid 80's[6,7]. Busse reported recent results based on his work at the University of Stuttgart[8] and an ultrasonic assisted thermal method is being developed by Wayne State University[9] under FAA and other funding. The method uses a short single pulse of low frequency (on the order of 10 to 40 kHz) ultrasound to "heat up" cracks and make them visible in the infrared range. Indigo Systems[10] has a commercial system available which is being investigated by Thompson[11] for

[4] SAE 2647

[5] www.cnde.iastate.edu/casrfpi.html

[6] Imaging of Mechanically Induced Thermal Heat Pattern, Edmund G. Heneke, III, QNDE 5A pp.447-454.

[7] Vibrothermographic NDE of Fibrous Composites, S. S. Russell, S. S. Lin and E. G. Heneke, QNDE 7B, pp. 1101-1107.

[8] J. Rantala, D. Wu, A. Salerno, and G. Busse, QIRT 96 – Eurotherm Series 50 – Edizioni ETS, Pisa (1997), pp. 389-393.

[9] R. Thomas, "Review of Thermal Methods", Review of Progress in Quantitative NDE Plenary Presentation, July 2002.

[10] http://www.indigosystems.com/

[11] J. Thompson, ASNT Presentation, Spring 2001.

commercial aircraft applications. Because of the potential benefits from this technique significant research efforts are underway in both experimental and theoretical studies. Work underway with US Navy funding is exploring the use of strain gages and laser vibrometry to quantify displacements that occur during the excitation and their relationship to infrared emittance[12] in addition to process parameter studies[13]. Others[14],[15] are also using laser vibrometry to quantify surface displacements and correlate the results to thermal signal response. Limited POD data has been generated[16] in laboratory conditions on typical coupons used for FPI and eddy current POD studies. While considerable work is underway, additional information on the sensitivity and applicability of this technique to engine components and alloys is needed prior to wide-spread use in the aviation industry.

The basic premise of the thermal acoustic or sonic IR method is to use an external energy source with recent efforts using an ultrasonic horn originally intended for use in ultrasonic welding to excite the component. The external energy source causes an increase in local heating which is detectable with infrared cameras typically used in thermographic inspection. While preliminary results are promising, additional knowledge is needed prior to application to critical aviation components such as engine disks. The purpose of this program is to provide additional data to determine applicability of this method to engine components.

Objectives

- To evaluate the applicability of thermal acoustic inspection methods for engine materials and components including studies of the process parameters and their relationship to inspection effectiveness
- To assess the potential of thermal acoustic methods to induce damage in the component and/or cause additional crack initiation/growth
- To develop preliminary process specifications and associated POD curves.

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[12] W. R. Davis, M. B. Rankin, “Laser Vibrometry and Strain Gage Measurements of Thermosonic Activiation”, Review of Progress in Quantitative NDE, Vol. 22a, pg. 492, 2003.

[13] I. Perez and W. R. Davis, “Optimizing the Thermosonics Signal”, Review of Progress in Quantitative NDE, Vol. 22a, pg. 505, 2003.

[14] X. Han, L.D. Favro, and R. L. Thomas, “Recent Developments in Sonic IR Imaging”, Review of Progress in Quantitative NDE, Vol. 22a, pg. 500, 2003.

[15] D. Raulerson, J. Lively, X. Ouyang, K. Smith, internal PW protocol for thermal acoustic measurements.

[16] Work performed by Pratt & Whitney on NASA Turbine Engine System Technology (TEST) Contract # NAS3-98005, Task Order # 21, "Development and Integration of Inspection Technology for Damage Detection in On-wing Engine Configurations".

Progress (through March 31, 2007):

Task 1: Develop Detailed Project Plan:

Subtask 1.1 – Project Planning:

The required Project plan was completed and submitted to FAA in November 2004. Updates were provided in November 2005.

Task 2: Damage Assessment:

Task 2 consists of a series of tasks to determine if any combination of the sonic excitation parameters could induce damage to typical jet engine rotating components such as disks, spools, spacers, rotating seals, etc. Most such components are made of either titanium or nickel base alloys. The behavior within each of these two alloy types is generally similar but is not so between the two. Because there are a myriad of distinct alloys used by the jet engine manufacturers, it was decided to limit the evaluation to a single titanium alloy and a single nickel base alloy. The alloys chosen are Titanium 6Al-4V and Inconel 718 because they are both widely used by all engine manufacturers, they are easy to obtain to industry standards, they are relatively inexpensive, and their properties are well known. Subtask 2.1 will establish experimental test plans and generate the samples for use in the damage assessment subtasks of 2.2 through 2.4.

Subtask 2.1 – Sample fabrication/acquisition:

The purpose of this subtask is to fabricate necessary samples and generate the protocols for materials characterization, mechanical testing, and thermal acoustic measurements. Materials characterization data will be documented and can also be used to suggest appropriate process sensing approaches for those conditions deemed to be detrimental to part life and which serve as crack initiation sites.

Localized damage samples: To investigate for potential localized damage from the excitation source (items 1 – 4 above), a sample design of 3”x 1”x 0.25” was selected in the prior GE program, FAA Contract No. DTFA03-02-C-00049[17] and fabricated. This set of 48 (24 of each alloy) unused samples was determined to be acceptable specimens for use in the current program. Sample fabrication activity associated with this sample type is complete.

High cycle fatigue samples: A rectangular hour glass shaped HCF sample that meets ASTM E466 has been chosen for the HCF study. The selection was based on choosing a standard HCF configuration that would also provide an acceptable flat surface for excitation with the horn. Sample fabrication activity associated with this sample type is complete.

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[17] FAA Final Report, “Sonic Infrared Inspection of Aircraft Rotating Parts”, FAA Contract No. DTFA03-02-C-00049, submitted December 2003.

Progress This Quarter:

Low cycle fatigue samples: Crack growth and baseline characterization of all the LCF specimens is now complete. No additional sample fabrication activity will be needed.

Subtask 2.2 – Localized Damage Characterization:

The purpose of this subtask is to assess whether localized damage occurs which is detrimental to the sample as part of the generic thermal acoustic inspection process. Using sample characterization protocols established in Subtask 2.1, baseline characterization of the 3" x 1" x 0.2" samples will be completed. DOE procedures will be used to design a systematic assessment of the thermal acoustic parameters within the bounds set above. Samples will then be exposed to the excitation source and measurements of displacement made using laser vibrometry. Upon completion of the exposure to the excitation source, the CP will be followed to complete post characterization of samples. If no damage is detected, additional excitation cycles will be imposed on at least some of the samples. This additional exposure will provide data regarding the occurrence of damage in "out of limit" conditions. The need for additional testing will be assessed at this time and a recommendation made to FAA. Additional samples will be generated as necessary.

Progress This Quarter:

Characterization work was completed on twelve Ni and Ti specimens. White light photographs, laser profilometer scans, X-ray diffraction measurements and micro hardness measurements were made at the areas of contact. Due to the cost, X-ray diffraction measurements were not made on all specimens. A subset of specimens was chosen based on visual damage seen for X-ray diffraction measurements and hardness measurements. This data is summarized in (Table 1). In most experiments the flat tip caused more surface changes based on the laser profilometer results than the rounded or spherical tips but did not provide any additional energy in the specimens. The changes seen with the laser profilometer when using the flat tip are mainly at the edges where tip gouging occurs (Figure 1). This seems to be caused when the tip is not exactly perpendicular to the specimen surface and the sharp corners of the tip catch and are driven into the specimen. Based on this data it has been decided to eliminate the flat tip in future experiments. Another result of the study was that using #90 paper coupling only reduced the specimen energy by a small amount verses using no coupling. The use of coupling reduced the changes in depth seen by the laser profilometer to immeasurable levels in all but one experiment where a point left on the spherical tip during manufacturing burnt through the coupling paper and caused an indentation. Typical laser profilometer results from the rounded and spherical tips are shown in (Figure 2 & 3). This data will be used to determine operating parameters for exciting the LCF and HCF specimens.

Table 1. Localized damage specimen characterization results.

Specimen	System	Tip type	Coupling	Load Force (lb)	Amplitude (%)	HAE (m^2/sec)	Stress Change Width (Ksi)	Stress Change Length (Ksi)	Depth (uM)	Hardness Change (HRC)
Ti64-23B	PW	Flat	N	40.00	40.55	0.70	-95.2	-52.6	13	10
Ti64-16B	GE	Flat	N	30.00	40.00	0.79	20.3	-6.0	5	0
Ti64-23T	PW	Flat	Y	49.50	45.78	0.96			0	
Ti64-16T	GE	Flat	Y	30.00	40.00	0.69			0	
Ti64-13B	PW	Rnd	N	35.00	25.00	0.65	-76.1	-45.5	3	1
Ti64-15B	GE	Rnd	N	30.00	40.00	0.68			6	
Ti64-13T	PW	Rnd	Y	49.20	27.60	1.03			0	
Ti64-15T	GE	Rnd	Y	45.00	40.00	0.80			0	9
Ti64-21B	PW	Sph	N	35.00	70.00	0.39			4	
Ti64-20B	GE	Sph	N	45.00	70.00	0.95	-25.7	-3.9	0	
Ti64-21T	PW	Sph	Y	35.00	67.75	0.41	3.5	-3.5	0	
Ti64-20T	GE	Sph	Y	45.00	70.00	1.64			0	4
In718-19T	PW	Flat	N	35.00	30.00	3.79			13	-6
In718-17T	GE	Flat	N	40.00	65.00	0.27			5	3
In718-19B	PW	Flat	Y	40.00	35.00	3.65			0	
In718-17B	GE	Flat	Y	60.00	70.00	0.63			0	
In718-13B	PW	Rnd	N	30.00	30.00	0.84	-176.2	-75.6	3	0
In718-12T	GE	Rnd	N	40.00	60.00	0.81	-147.7	-47.2	6	
In718-08T	PW	Rnd	Y	40.00	40.00	1.01			0	
In718-12B	GE	Rnd	Y	60.00	80.00	0.81			0	
In718-14T	PW	Sph	N	40.00	60.00	2.17	-12.5	-133.4	20	
In718-11T	GE	Sph	N	50.00	70.00	0.59	-102.6	-15.1	3	
In718-14B	PW	Sph	Y	40.00	51.45	3.63			3	
In718-11B	GE	Sph	Y	50.00	70.00	0.60			0	

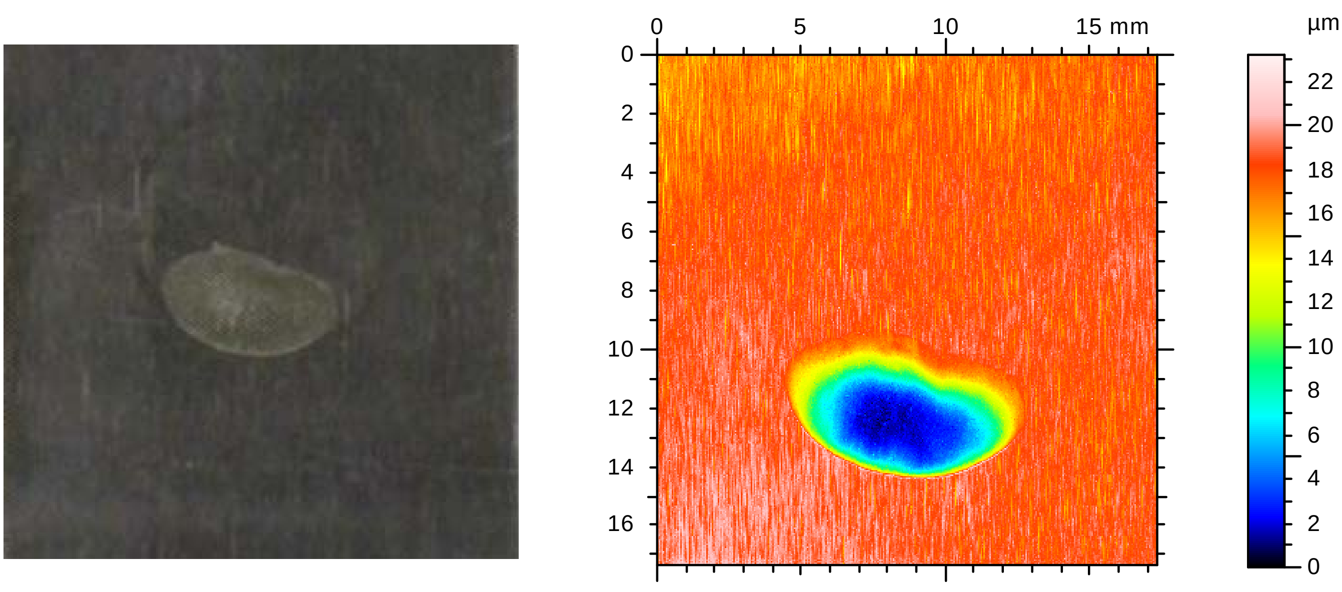

Figure 1. Flat tip without coupling showing edge gouging, In718-19 Top.

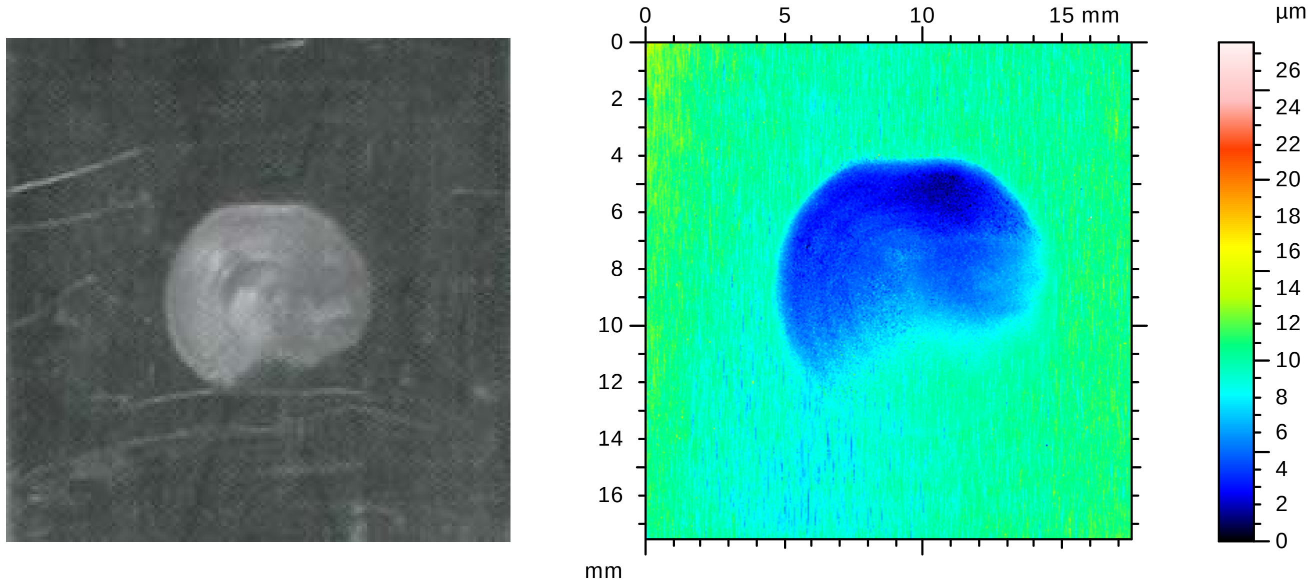

Figure 2. Rounded tip without coupling (flat area is wrench grip), In718-12 Top.

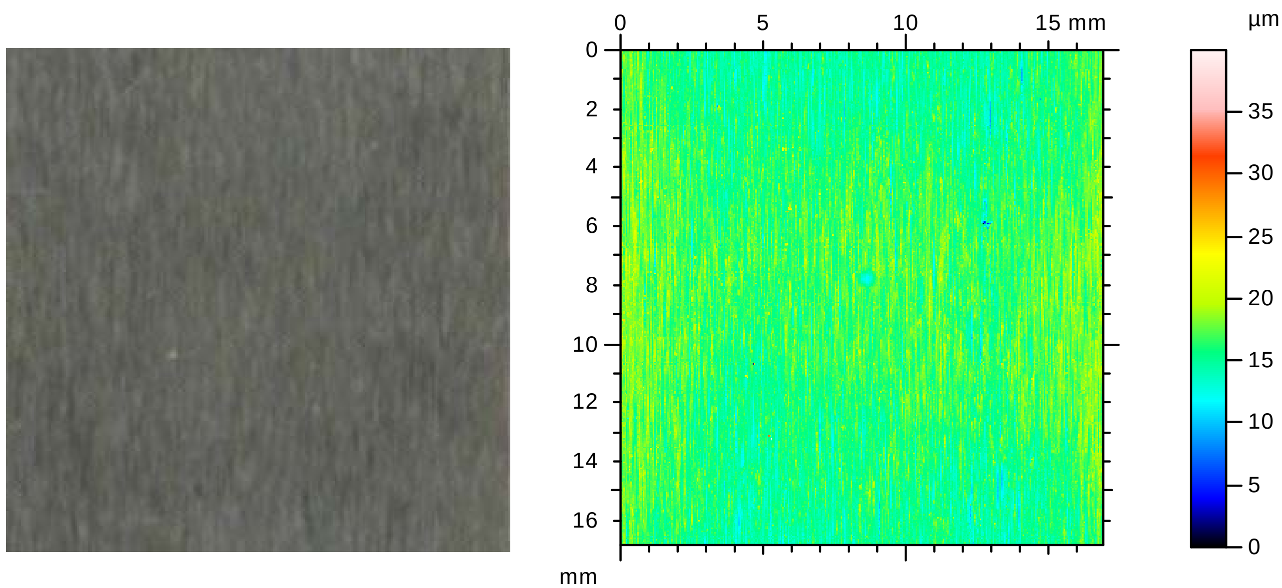

Figure 3. Spherical tip without coupling, Ti64-21 Bottom.

Subtask 2.3 – Crack Initiation and Fatigue Life Debit Assessment:

The purpose of this subtask is to assess whether damage occurs which can lead to crack initiation or otherwise contribute to a fatigue life debit. To assess the potential of this damage, a set of samples were fabricated in subtask 2.1 which are in compliance with ASTM testing configurations for high cycle fatigue. The specimens have been manufactured (see subtask 2.1) and a test plan generated.

Progress This Quarter:

As reported previously, an unusually large number of samples have broken at the transition radius rather than in the gage of the specimen. Therefore, ETC has considered several sample modifications. The first test added a pin option as shown in Figure 4.

The pinned specimen designed to eliminate possible slippage failed at Metcut at the edge of the radius transition (Figure 4). There was also a failure of the pins during the test. The midlife failure of the pins and the clevises lead to question validity of the results. It was decided to break the corner edges of six samples and test those at ISU.

Figure 4. Pinned HCF specimen with edge radius transition failure.

Metcut completed machining 0.020” radiuses on the six additional Ni specimens to break all of the corner edges. ISU fatigued the specimens at 132.5Ksi and an R ratio of 0.1. The results are shown in (Table 2):

Table 2. Ni HCF specimen fatigue life with 0.020" corner radius.

Specimen	Cycles (K)	Failure Location
2	264	Transition edge
3	165	Transition middle face
61	221	Transition middle face
98	232	Gage center
99	10000	Ran to life
102	329	Transition (undetermined start)

These results are better than previous results at Metcut. It is the team's opinion that the transition middle face breaks (Figure 5, left) are valid and the SN data looks good. However, there are still concerns with transit or edge breaks such as Figure 5, right. FEM analysis was used to determine a taper geometry that would shift the high stress point to the gage section.

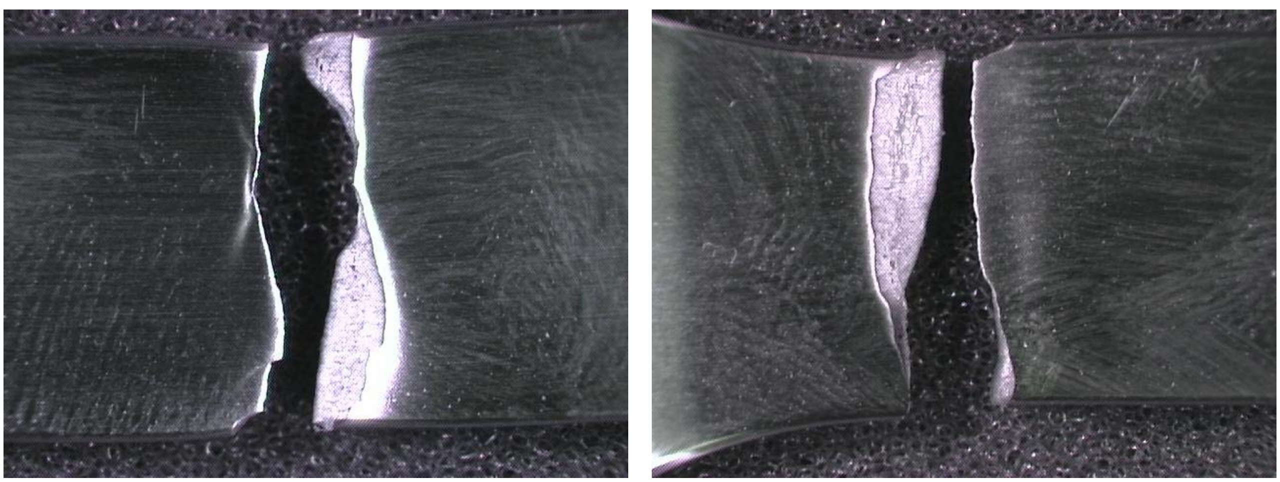

Figure 5. Gage break #98 (left), Middle radius transition break #3 (right).

Metcut has begun machining the 6 Ni tapered specimens. These specimens will have a 34mil reduction in gage width on each side of the specimen based on FEM results. FEM modeling of this configuration shows no stress concentrations near the edges of the specimen. A continuous radius will be machined from the existing radius transition through the gage area to the transition radius on the other side to create an hourglass shaped gage cross section. As soon as these specimens are completed they will be sent to ISU for fatiguing.

Subtask 2.4 –Crack growth assessment:

The purpose of this subtask is to assess whether crack growth of a pre-existing flaw can occur which is detrimental to the sample as part of the generic thermal acoustic inspection process. A preliminary round robin comparison of capabilities at each of the ETC partner organizations will be done to enable comparable thermal acoustic measurements at multiple locations. Laser vibrometers will be used to arrive at similar displacement levels given that the experimental setup at each of the organizations has slight variations. Samples will be characterized to establish baseline properties. Using guidance from the DOE in Subtask 2.1 and results of the screening DOE in subtask 2.3, samples will be exposed to a range of thermal acoustic process parameters. Upon completion of the thermal acoustic exposure, post characterization measurements will be made. Included in this subtask will be quantitative FPI measurements using brightness and UVA image capture using methods developed in the CASR FPI program. The brightness and UVA image data will provide some indication of changes in the crack characteristics.

The baseline characterization of these specimens is complete. Additional testing will begin upon completion of subtask 2.2. Results of subtask 2.2 will be used to guide the experimental plan for this subtask.

Progress this quarter:

Vibrothermography work with the LCF crack samples began this quarter. ISU evaluated the GE, PW and ISU black coatings to determine sensitivity and usability of each. Based on the repeat excitations we will be doing, the recommendation was made to use the PW product since it adheres to the specimens better and will last longer. The recommendation was also made to only coat the 1” x 1” area around the crack to prevent the coating from getting underneath the exciter tip and the clamping pins.

The initial tests of the two LCF Ni and Ti specimens selected for the natural frequency and sensitivity tests were completed. The ISU system using a frequency of 14KHz and HAE energies of 0.15 on the Ni and 0.07 on the Ti specimen was able to find both ~0.080” length cracks. Using the conservative loading and amplitude parameters chosen for the PW system only one test found the crack during the first round of tests. The PW loading and amplitude parameters were increased until both cracks were detected. The PW system was run using the spherical and rounded tips using both coupling and no coupling. The specimens will be checked for localized damage and crack growth on return to ISU. Examples of the thermal images are provided below in Figures 6 through 17. The crack image is shown in the center. There are artifacts from the excitation source also shown in some raw images which appear as a circular shape. In some images, the paper used as the coupling media shows up as seen to the right in Figure 6. A raw image and processed image are shown for each test condition. The test conditions are listed in the figure caption.

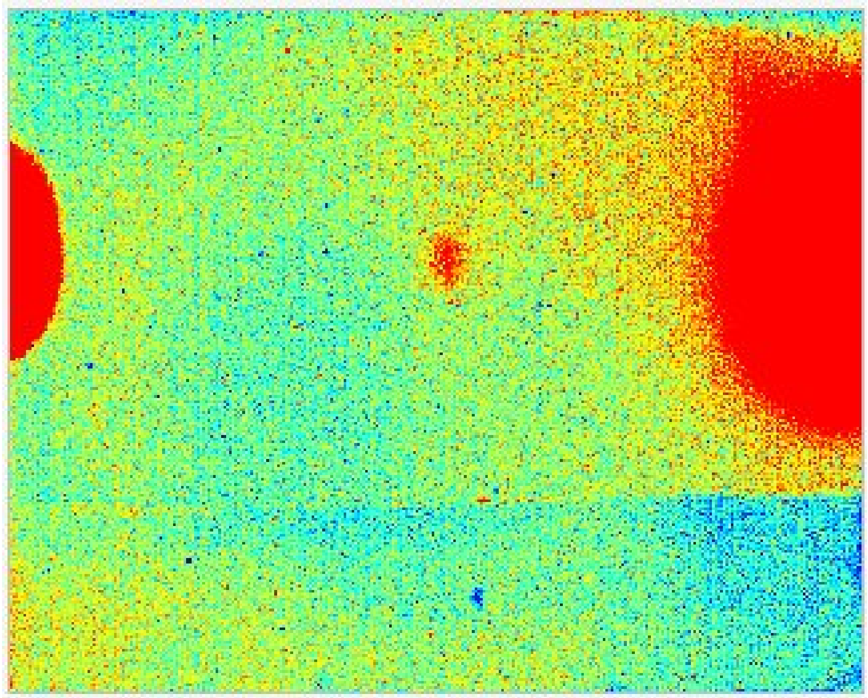

Figure 6. Sample: 05-065, Using Round Corner tip, W/O paper, 50lbs loading, 55% amplitude, 160J, Raw IR image.

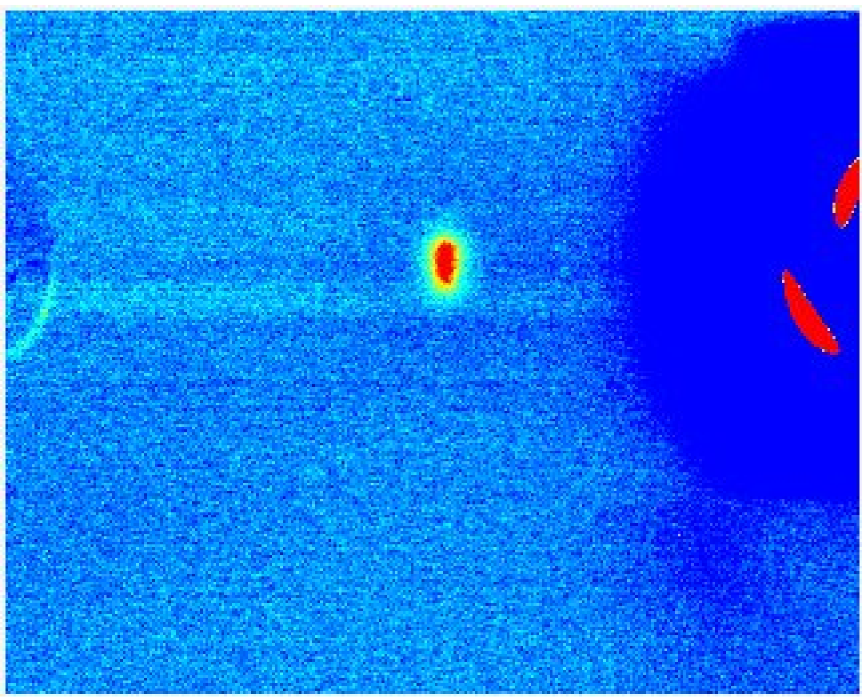

Figure 7. Same data as above Fig. 1, PW processed image

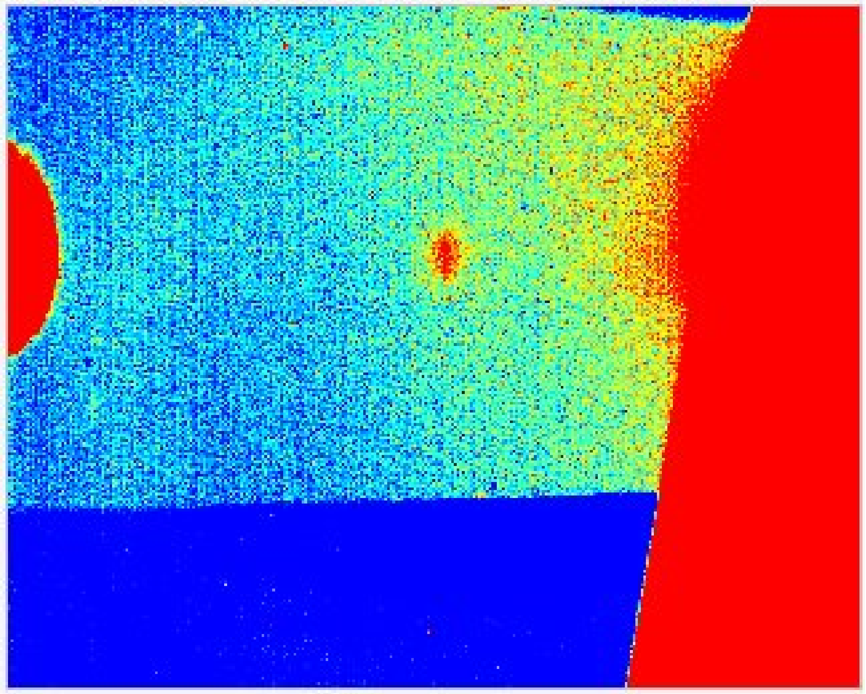

Figure 8. Sample: 05-065, Using Round Corner tip, W/ paper, 50lbs loading, 55% amplitude, 114J, Raw IR image.

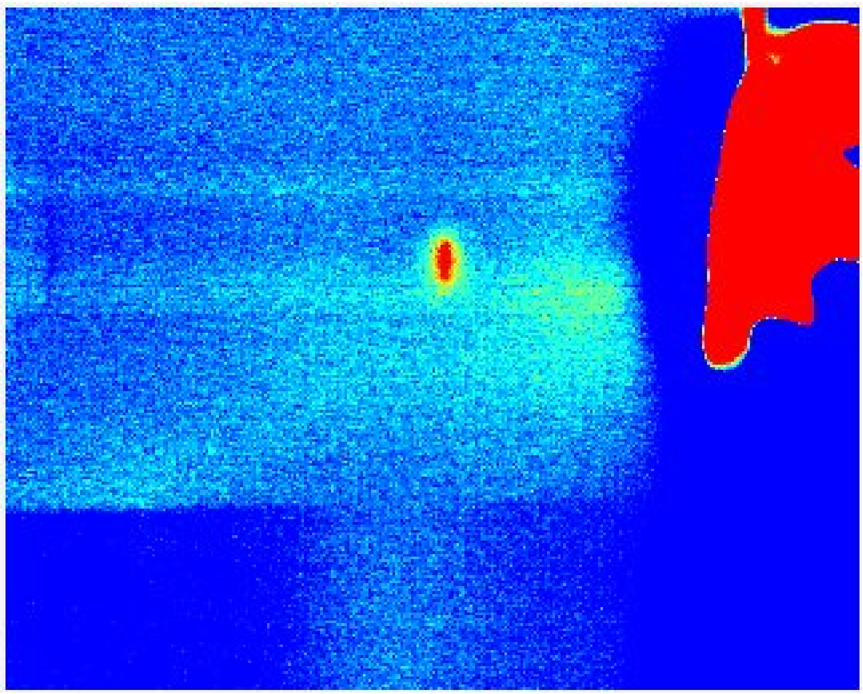

Figure 9. Same data as above Fig. 3, PW processed image

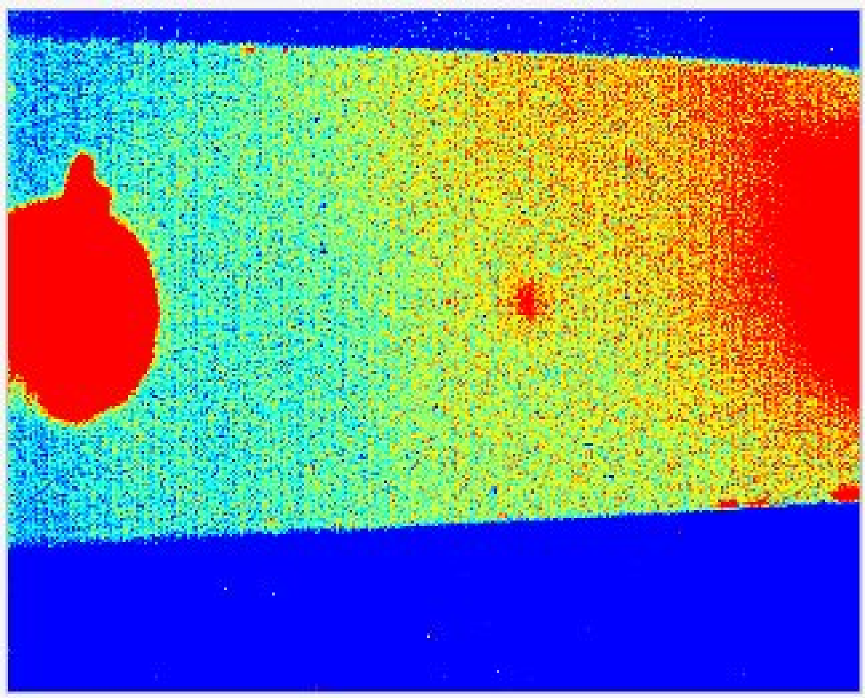

Figure 10. Sample: 05-407, Using Round Corner tip, W/O paper, 50lbs loading, 55% amplitude, 380J, Raw IR image.

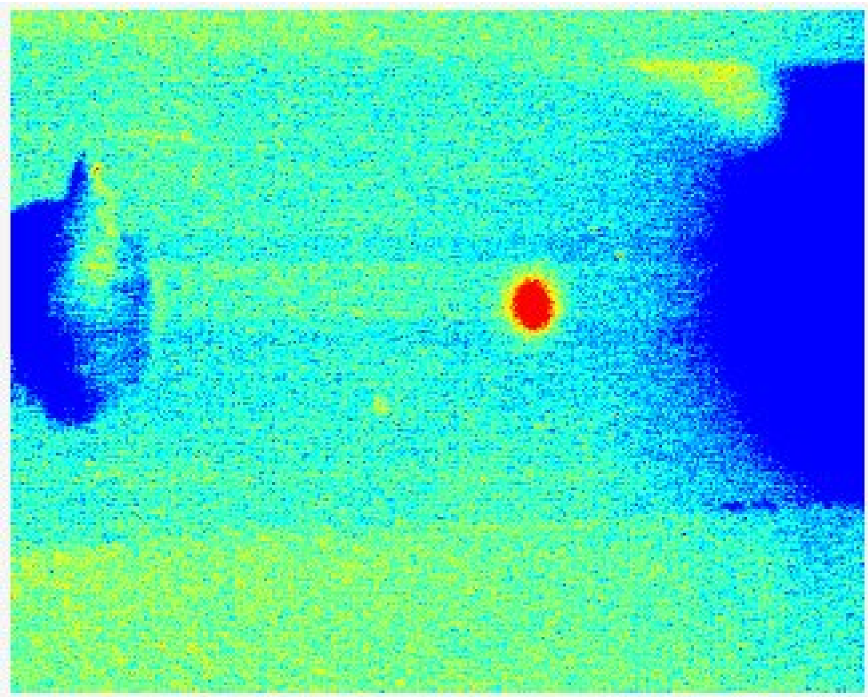

Figure 11. Same data as above Fig. 5, PW processed image

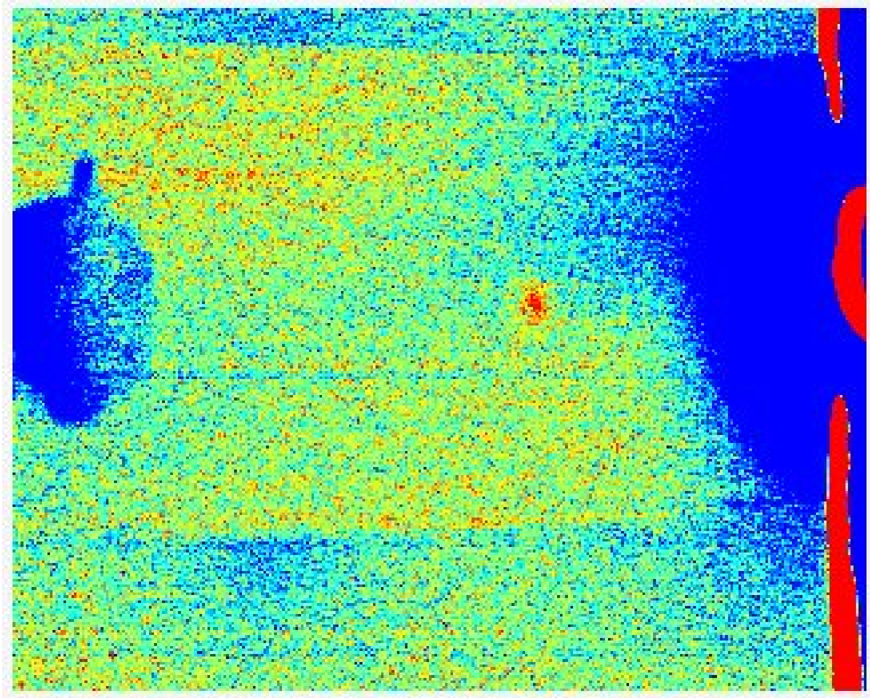

Figure 12. Sample: 05-407, Using Round Corner tip, W/ paper, 50lbs loading, 55% amplitude, 361J, PW processed image. Didn't see crack in raw IR image.

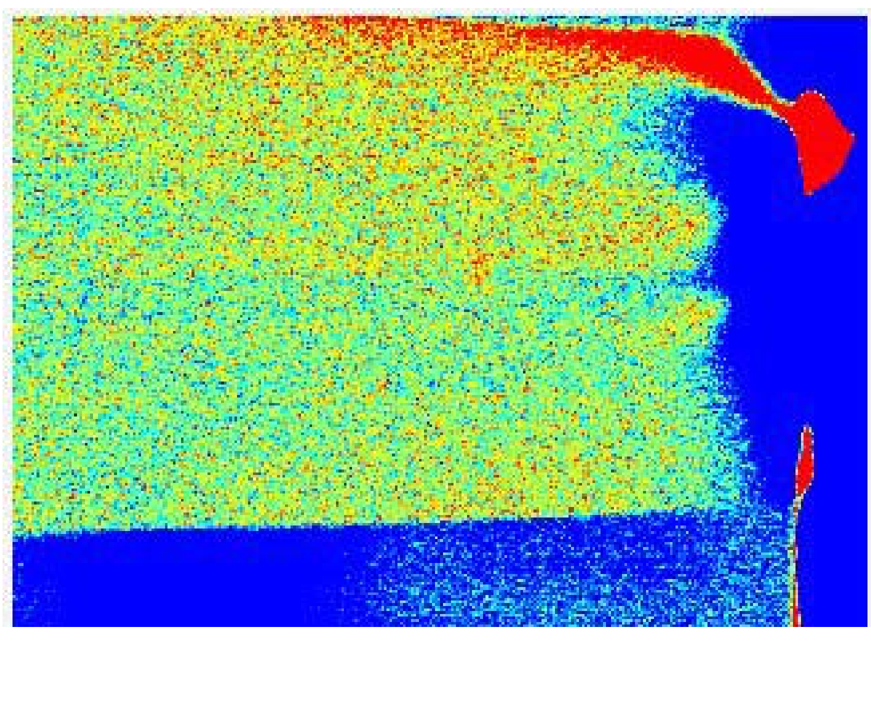

Figure 13. Sample: 05-065, Using Spherical tip, W/ paper, 50lbs loading, 65% amplitude, 158J, PW processed image. Didn't see crack in raw IR image.

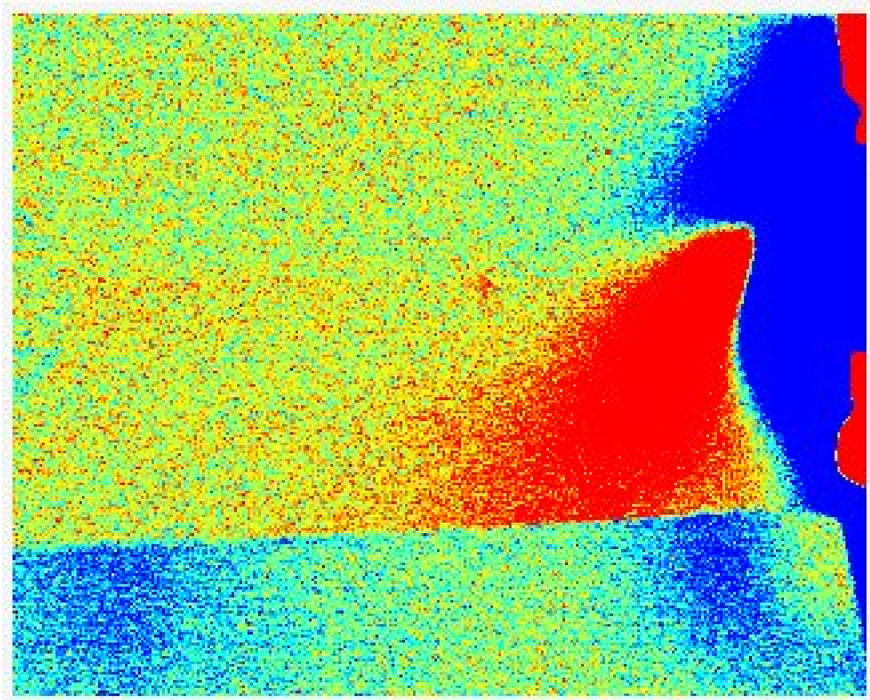

Figure 14. Sample: 05-407, Using Spherical tip, W/ paper, 50lbs loading, 65% amplitude, 109J, PW processed image. Didn't see crack in raw IR image.

Vibrometry data was also captured for each of the images and is provided in Figures 15 through 19 below. The test conditions are included in the figure captions and can be matched to the thermal images in Figures 9 through 14.

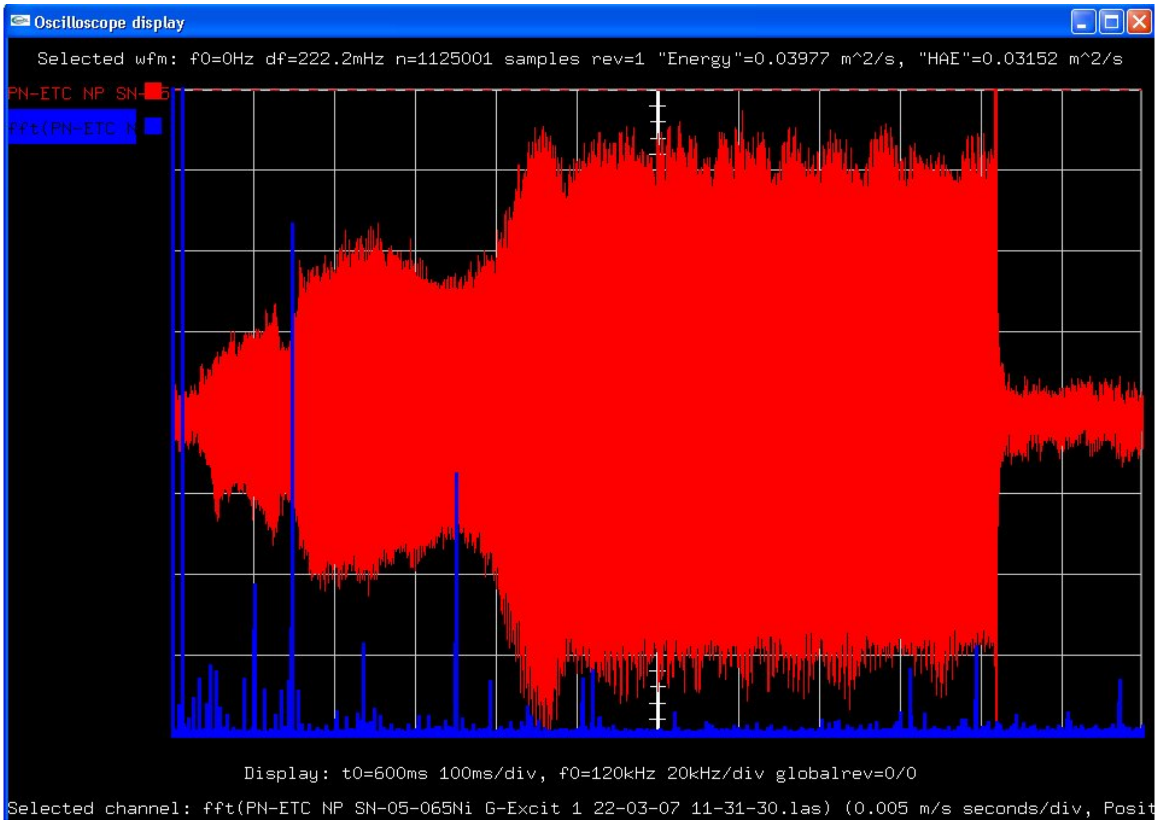

Figure 15. Sample: 05-065, Using Round Corner tip, W/O paper, 50lbs loading, 55% amplitude, 160J, Laser vibrometer data.

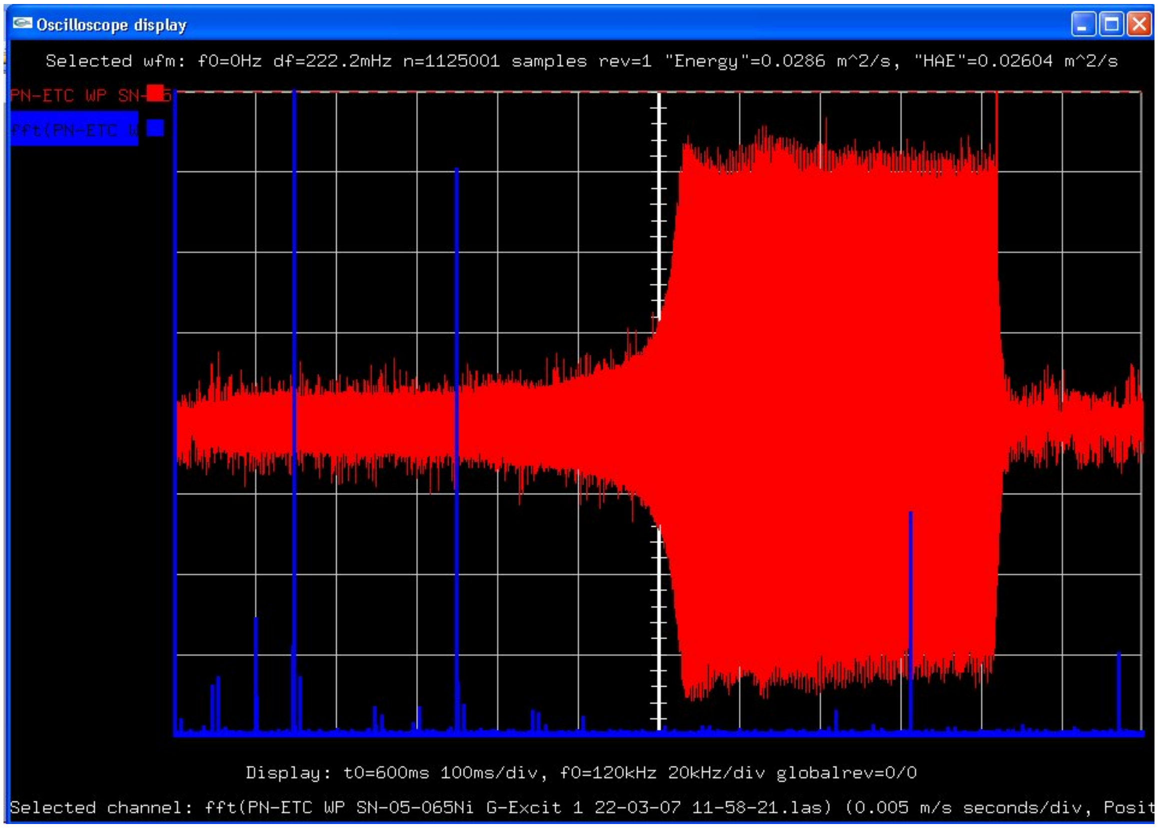

Figure 16. Sample: 05-065, Using Round Corner tip, W/ paper, 50lbs loading, 55% amplitude, 114J, Laser vibrometer data.

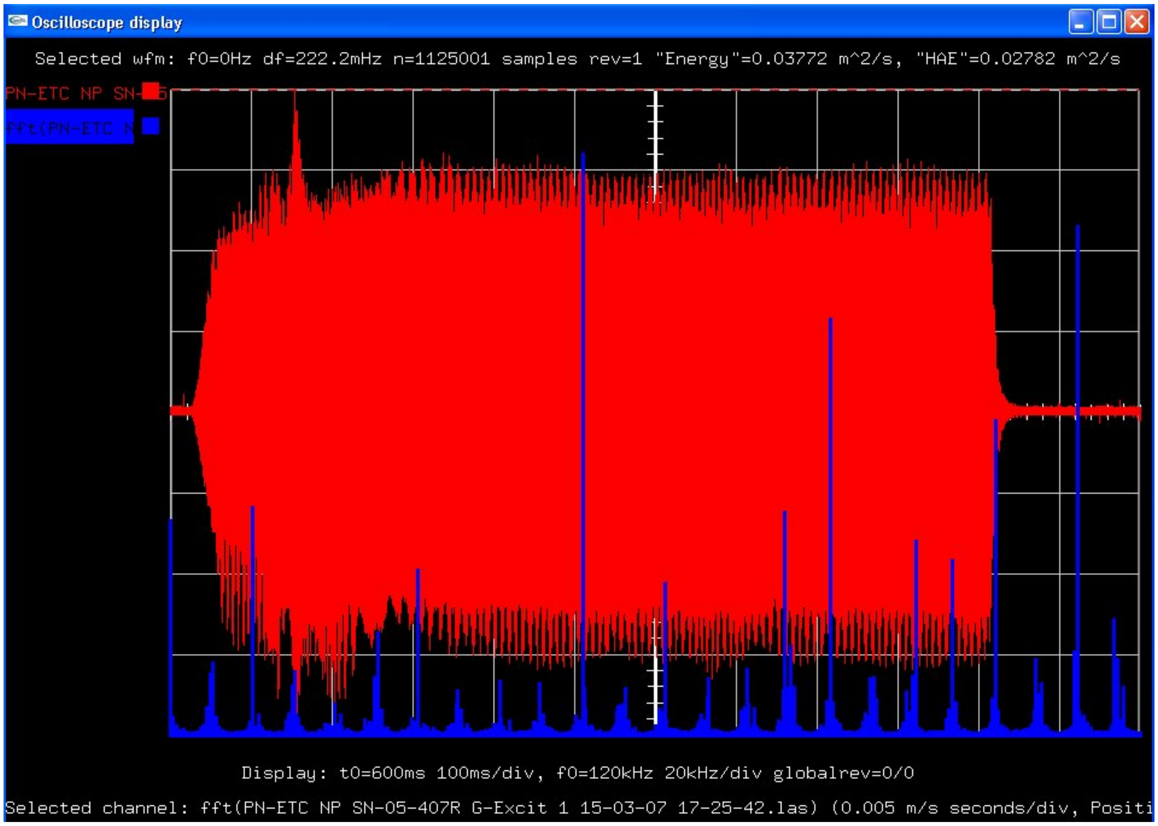

Figure 17. Sample: 05-407, Using Round Corner tip, W/O paper, 50lbs loading, 55% amplitude, 380J, Laser vibrometer data.

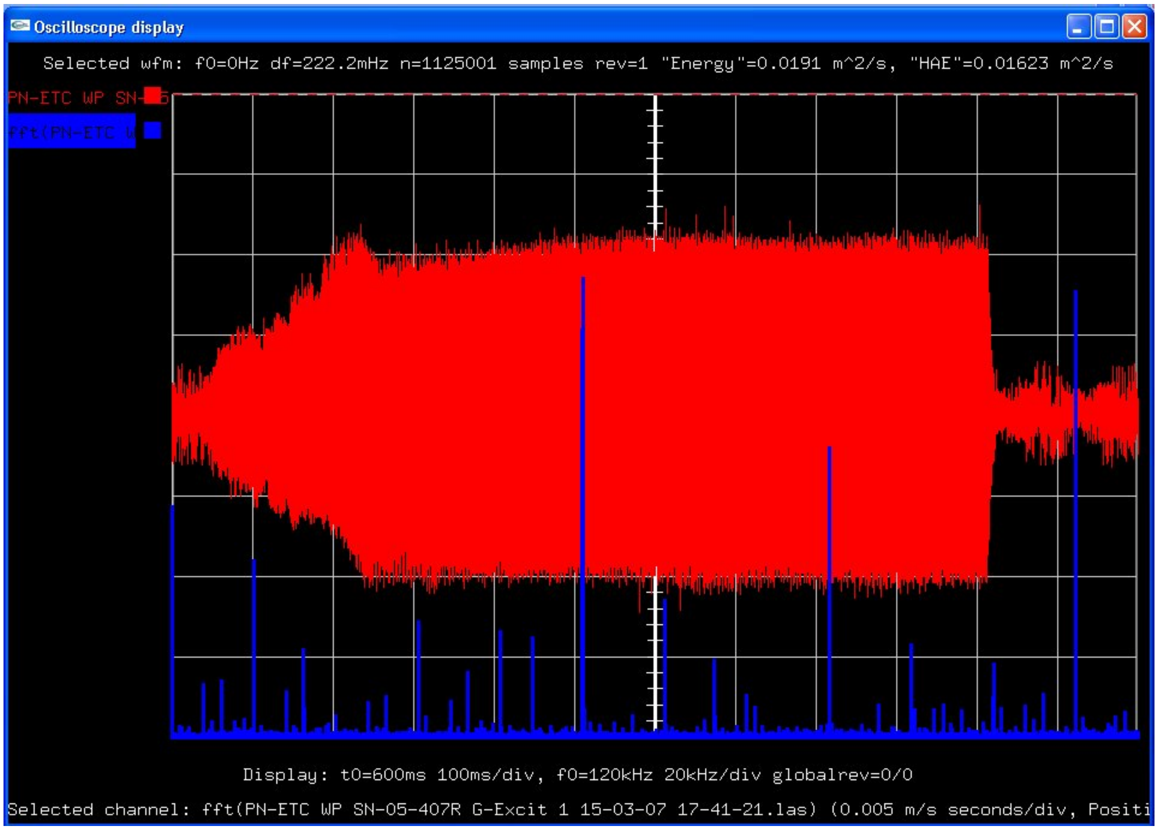

Figure 18. Sample: 05-407, Using Round Corner tip, W/ paper, 50lbs loading, 55% amplitude, 361J, Laser vibrometer data.

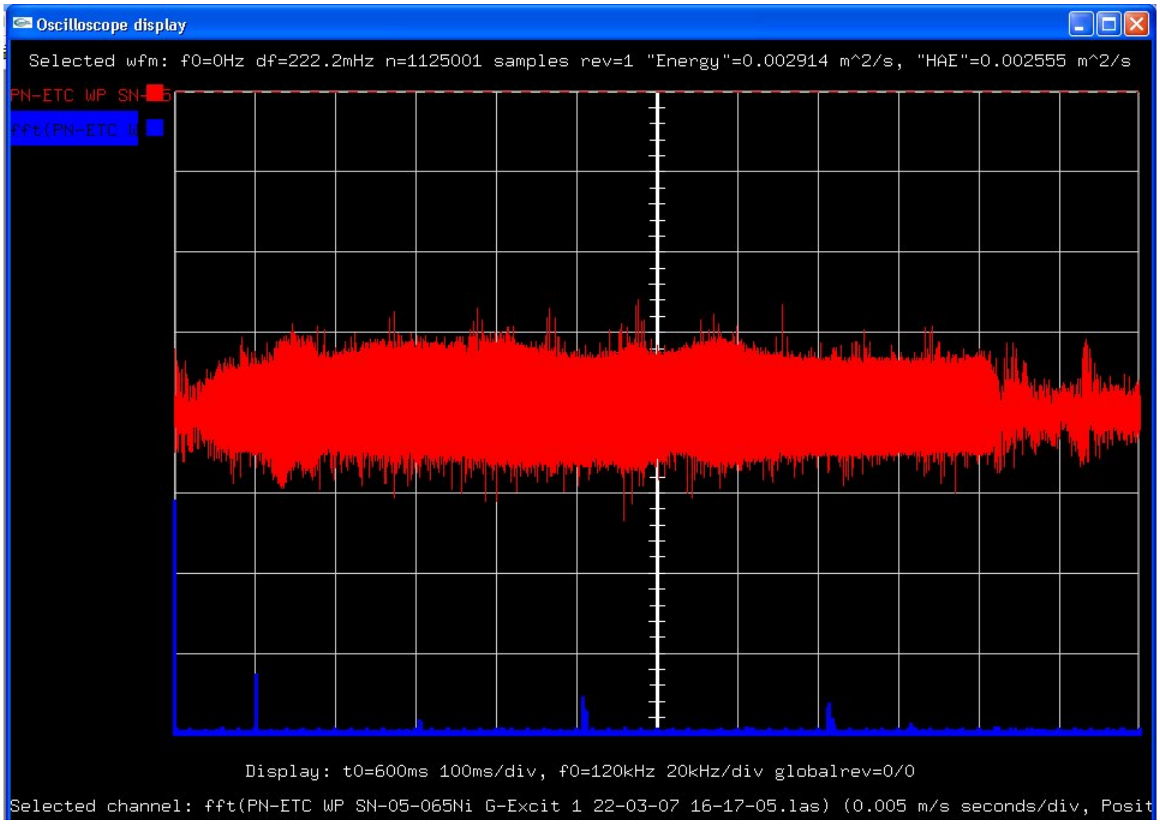

Figure 19. Sample: 05-065, Using Spherical tip, W/ paper, 50lbs loading, 65% amplitude, 158J, Laser vibrometer data..

Subtask 2.5 – Documentation of Damage Characterization Studies

A preliminary summary of the damage characterization studies will be prepared for incorporation into the final report.

Task 3: NDE Process Development and Enhancement

Subtask 3.1 – Process optimization:

As with all inspection methods, parameter selection and optimization is critical to the final performance. Understanding the relationship between the inspection parameters and the performance of the technique at a fundamental level is a necessary step in order for wide-spread implementation to occur. The extent to which individual parameters affect the sensitivity of the thermal-acoustic inspection requires investigation. Samples being fabricated in Task 2 will be used for this study which is on hold per FAA direction.

Subtask 3.2 – Application to actual parts:

In addition to improved understanding using sample coupons, experience applying the technique to a variety of hardware is needed. Each of the OEMs will determine if internal sources can supply hardware with defects to the program with the likely arrangement being a temporary loan. AANC and the Air Force will also be contacted as potential sources of components. To the extent possible, i.e. as geometrical features will allow, defects will be characterized prior to and after excitation. Process parameters developed in Task 2 and Subtask 3.1 will be applied to the actual hardware. Laser vibrometry measurements will be made to compare to displacements in earlier crack panel studies. Sensitivity to crack detection will be assessed. This study is not scheduled to begin until February 2007.

Subtask 3.3 – Documentation of Process Optimization Studies

A preliminary summary of the process optimization studies will be prepared for incorporation into the final report. The summary will include results on both coupons and actual hardware. This study is not scheduled to begin until April 2007.

Task 4: Quantitative Validation of Technique Performance

Implementation of any inspection method relies on quantification of the performance of the technique such that the detectability of the defects of interest is well known. Given quantification data, often in the form of probability of detection results, and knowledge of the component to be inspected, e.g., geometry limitations, an inspection method or methods are selected to ensure continued safe operation. Limited POD data has been generated for this method and is complicated by the requirement to utilize images in the decision process. This task will address POD consideration for this new method.

Subtask 4.1 – Quantification of Technique Performance

As a first step, the prior work for this method is being reviewed. As with any image based method, a critical factor in the effectiveness of method is the processing approaches used to evaluate the digital data. A POD working group has been established to assist in sample design as applicable, to guide data acquisition and analysis, and to provide reliability/performance estimates. AANC personnel will be sought for input into the selected approach. Interim data will be gathered during the program to assist the POD working group with development and validation of data quantification methods. Effort to date has primarily been limited to literature review by the doctoral candidate working on this project. Further work is on hold until FAA approval is provided.

Subtask 4.2 – Validation of Technique Performance

At the conclusion of the process optimization studies in Subtask 3.1, formal POD studies will be completed to provide validation data of technique performance. Specific recommendations will be made regarding the analysis of image based data. Comparisons to prior FPI studies will be documented. This task is not scheduled to begin until February 2007.

Subtask 4.3 – Preliminary Process Descriptions for NDE Enhancements

Based on the results of the program, preliminary process descriptions will be generated. Details will be of sufficient quality to enable individual OEMs to generate internal specifications as applicable to their product. This task is not scheduled to begin until May 2007.

Task 5: Final Report

Subtask 5.1 – Final Reporting

Draft and final report that includes results and conclusions of Tasks 2 through 4 will be prepared. This task is not scheduled to begin until May 2007.

Plans for the Next Quarter:

- Fatigue tapered HCF specimens
- Cut the two LCF natural frequency specimens to excite natural frequency and excite at both ISU and PW
- Finalize LCF and HCF testplans
- Begin sensitivity tests on LCF specimens

Deliverables List

Description	Delivery Date	Status
Deliverable 1.1: A detailed project plan will be delivered within 30 days of completion of the subcontracting process with the OEMs. This plan will include a Gantt chart generated by Microsoft Project depicting tasks, milestones, and critical path. The project plan will be prepared and delivered via email and/or CD-ROM.	November 2004	11/04 – First generation plan delivered to FAA.
Deliverable 1.2: An initial project review will be conducted at a mutually agreed upon location. Notification of the dates and logistics of the meeting will be communicated to the FAA project monitor within five days of establishment of the subcontracts with the OEMs.	December 2004	12/04 – Meeting held December 3 -4, 2004 in Washington DC. Deliverable complete.
Deliverable 2.1: Provide approximately sixty 6” x 1” x 0.5” samples for use in thermal acoustic studies. Samples will contain lcf cracks in a range of sizes to be determined during the program.	September 2005	6/05 – Sample fabrication is complete.
Deliverable 2.2: Provide approximately one hundred samples for hcf testing, fifty of each of two alloys.	May 2006	6/06 – 105 samples of Ti and Ni machined into HCF specimens and characterized.
Deliverable 2.3: Provide characterization protocol (CP) for use in pre and post assessment of sample condition. Provide mechanical testing protocol (MTP) for use in high cycle fatigue testing. Provide a thermal acoustic experimental protocol (TAEP) to define the experimental setup and measurement process to be used during the program. Included in the protocol will be use of laser vibrometry to assess displacement.	March 2006	3/06 - HCF mechanical test plan and characterization test plan defined. Laser vibrometer data collection and analysis method defined.
Deliverable 2.4: Materials characterization data before and after thermal acoustic excitation at the point of excitation.		6/06 – Precharacterization data collected on localized damage, LCF and HCF specimens.
Deliverable 2.5: Mechanical test plan and resulting data.		
Deliverable 2.6: Materials characterization data before and after thermal acoustic excitation. Samples used in this study will contain preexisting lcf cracks.		6/06 – Precharacterization data collected on localized damage, LCF and HCF specimens.

Description	Delivery Date	Status
Deliverable 2.7: Conduct a program review with the FAA that summarizes the results of the damage characterization studies. The review will be held at a mutually acceptable location with the TFP, PF, and FAA representatives identified by the FAA project monitor.		
Deliverable 2.8: Provide preliminary summary of the damage characterization study results in a format for easy incorporation into the final report.		
Deliverable 3.1: Conduct a review meeting with FAA.		On hold per FAA contractual direction.
Deliverable 3.2: Conduct a review meeting with FAA.		On hold per FAA contractual direction.
Deliverable 3.3: Provide recommended parameter specifications for thermal acoustics inspection of titanium and nickel materials.		On hold per FAA contractual direction.
Deliverable 3.4: Provide preliminary summary of the process optimization results in a format for easy incorporation into the final report. The summary will include data from coupons and engine hardware.		On hold per FAA contractual direction.
Deliverable 4.1: Summary of POD approach and POD curves including all data used to generate the POD curves.		On hold per FAA contractual direction.
Deliverable 4.2: Preliminary process descriptions of the enhanced NDE TA technique that can be utilized by OEMs		On hold per FAA contractual direction.
Deliverable 5.1: Draft final and final report including initial NDE technique evaluation and selection, a description of various defects studied, NDE technique development and optimization results, assessment of production readiness, and POD approach/results.		On hold per FAA contractual direction.

Key milestones

Task Description	Original Date	Revised Date	Status
Task 1: Develop Detailed Project Plan	11/04		Complete
Subtask 1.1. Conduct Initial Project Review	11/04		11/04 – First generation plan delivered to FAA.
Task 2: Assessment of the Potential of Damage from Thermal Acoustic Measurements			
Subtask 2.1 – Sample fabrication/acquisition			
Assess usability of existing 3" x 1" x 0.2" samples available at GE (24 ea. of Ti and Ni for a total of 48) for use in subtask 2.2.	1/05	5/05	5/05 – completed, had to regrind samples to 64rms surface finish from 175rms
Fabricate additional 60 samples each of Ti and Ni in 6" x 1" x 0.5".	6/05	7/05	6/05 – 180 samples complete with cracks
Generate at least 35 samples of each alloy for use in hcf testing. Samples will be sectioned from forged Ti-6-4 and Inco 718 disks. Additional samples will be sectioned as feasible to provide spares.	6/05	9/05	6/05 – forgings identified, based on additional technical discussions more samples are required (~105 / alloy) 9/05 – forgings acquired and initial ultrasonic characterization complete 11/05 – PO in place for disk cut-up and hcf testing 6/06 – complete, 105 samples of each alloy created and characterized.
Establish experimental protocol for sample characterization methods (CP) including optical/SEM microscopy, laser profilometry, hardness, and x-ray diffraction such that work can be performed at multiple locations with comparable performance.	1/05	7/05	6/05 – draft plan completed 3/06 – characterization plans completed
Establish experimental mechanical testing protocol (MTP) for hcf testing. Anticipate that ASTM approved processes will be used as appropriate	1/05	7/05	7/05 – HCF test plan completed
Complete measurements at multiple locations using 6" x 1" x 0.5" samples with cracks. Establish displacement measurement method which is expected to be the controlling "set-up" parameter. Establish experimental protocol to enable comparable thermal acoustic measurements (TAEP) at multiple locations in later subtasks.	3/05	12/05	6/06 – complete comparison and correlation studies at GE and PW.
Subtask 2.2 – Localized damage characterization	Does localized damage occur which is detrimental to sample		
Create DOE to determine process parameters to evaluate using	4/05	7/05	6/05 – draft test plan complete

Task Description	Original Date	Revised Date	Status
initial samples 3” x 1” x 0.2” samples.			
Complete baseline characterization using optical/SEM microscopy, laser profilometry, hardness, and x-ray diffraction.	4/05	8/05	6/05 – characterization begun 3/06 - complete
Using guidance from the DOE, expose samples to various process parameters.	7/05	12/05	9/06 – 12 samples complete
Complete initial damage characterization comparing to baseline measurements made in 2.1.	9/05	1/06	9/06 – characterization complete
Determine need for additional samples and/or additional sample configurations (different size, different curvature, etc.)	10/05	1/06	
Subtask 2.3 – Crack initiation and fatigue life debit assessment	Do cracks initiate and/or is there a life debit associated with the use of the TA method on pristine samples		
Complete baseline characterization using optical/SEM, laser profilometry, and x-ray diffraction.	9/05	12/05	6/06 - complete
Design the screening DOE		8/06	9/06 - complete
Using guidance from the DOE, expose 10 samples to various process parameters as part of screening DOE	10/05	9/06	9/06 – 12 samples complete
Analyze data from screening DOE and determine final experimental plan	12/05	10/06	9/06 – 12 samples being analyzed.
Using data from screening DOE, select three parameter sets that are believed to be representative of the lower, mid, and upper boundary conditions for actual component testing. Expose 5 samples of each alloy to each of three conditions for a total of 15 samples of each alloy and a grand total of 30. Care will be taken to minimize surface irregularities prior to excitation that would lead to variability in the hcf properties. .	2/06	12/06	
Complete initial damage characterization comparing to baseline measurements made in 2.1. A visual assessment of localized damage will be completed prior to hcf testing and surface condition documented for comparison to the post-condition.	4/06	2/07	
Complete HCF testing on samples without shot peening.	8/06	6/07	
Complete plan for assessment of samples exposed to shot peening.	9/05	10/06	
Expose shot peened samples to excitation per plan	2/06	12/06	
Complete initial damage characterization comparing to baseline	4/06	2/07	

Task Description	**Original Date**	**Revised Date**	**Status**
measurements made in 2.1. A visual assessment of localized damage will be completed prior to hcf testing and surface condition documented for comparison to the post-condition.			
Complete HCF testing on samples with shot peening.	9/06	6/07	
Determine need for additional samples and/or additional sample configurations (different size, different curvature, etc.). Fabricate, baseline characterization, TA measurements, post characterization.	Decision point 10/06	7/07	
Subtask 2.4 – Crack growth assessment	Do existing cracks growth associated with the use of the TA method on samples with pre-existing cracks?		
Complete baseline characterization using optical/SEM/acoustic microscopy, and laser profilometry.	9/05		9/05 – optical characterization of cracks complete
Using guidance from the DOE in subtask 2.1 and screening DOE in Subtask 2.3, expose samples to various process parameters.	3/06	1/07	2/07 – Initial Ni and Ti specimens excited
Complete post damage characterization comparing to baseline measurements.	6/06	4/07	3/07 – characterization completed on initial specimens
Measure FPI brightness and capture UVA image before and after TA exposure.	7/06	5/07	3/07 – white photographs completed
Subtask 2.5 - Documentation of Damage Studies			
Complete preliminary report of damage studies for incorporation into final report.	4/07	7/07	
Task 3 - Process optimization for typical disk geometries			
Subtask 3.1 – Process optimization in samples			
Study 1 - Develop a fundamental understanding of the mechanical energy interaction with a crack and subsequent thermal generation.			On hold per FAA contractual direction.
Collect experimental data (displacement measurements) and use numerical modeling tools to estimate stresses induced in simple geometries (rectangular specimen).	9/05		On hold per FAA contractual direction.
Develop analytical and numerical modeling tools to identify vibrational modes in simple geometries (rectangular specimen) and stress levels for the modes, for both transient and steady state conditions. Complete comparison of0 stress estimates from experimental data (displacement measurements).	12/05		On hold per FAA contractual direction.

Task Description	**Original Date**	**Revised Date**	**Status**
Use results of modeling study to assist with optimization of the process parameters	6/05		On hold per FAA contractual direction.
Provide analytical tools or "rules of thumb" for use in inspection development and implementation. Identify the appropriate response parameters to monitor and the method to monitor them, for verification of inspection functionality	8/06		On hold per FAA contractual direction.
Study 2 - Determine the variation of crack detectability with stress/strain & amplitude properties.			On hold per FAA contractual direction.
Complete fixturing capable of holding test samples that are simply supported and/or clamped at two points (whose separation can be varied) along the length will be constructed	6/05		On hold per FAA contractual direction.
Complete studies which vary clamping, excitation, and crack position points will be varied to obtain crack positioning at a range from nodal (maximum stress) to peak vibration (maximum strain) areas in samples with cracks of multiple sizes and morphologies. Determine the excitation power and amplitude at which cracks are no longer visible to IR.	12/05		On hold per FAA contractual direction.
Complete post characterization to determine if any changes in crack morphology occurred.	3/06		On hold per FAA contractual direction.
Using displacement from laser vibrometry measurements, develop test plan to establish the relationship of process parameters to sensitivity. Establish the parameter limits to prevent damage to samples.	8/06		On hold per FAA contractual direction.
Complete sensitivity study using samples with cracks (size distribution to be determined based on results generated in the program).	12/06		On hold per FAA contractual direction.
Subtask 3.2 – Application to actual parts			
Acquire several disks of each alloy with real cracks from either AANC or internal OEM sources. Apply process parameters from 3.1 and determine sensitivity to crack detection. Limited characterization of the parts for damage potential.	2/07		On hold per FAA contractual direction.
Subtask 3.3 – Data summation and interim reporting	4/07		On hold per FAA contractual direction.
Complete preliminary report of damage studies for incorporation into final report.	4/07		On hold per FAA contractual direction.
Task 4: Quantitative Validation of Technique Performance			
Subtask 4.1 – NDE Process Development Plan			

Task Description	Original Date	Revised Date	Status
Review existing PW data and use to guide systematic experimental design, such as process parameter effects, human factor effects, image analysis effects, etc.	6/05		On hold per FAA contractual direction.
Utilize process parameter limits establish in task 3 as input to experimental plan			
Subtask 4.2 – Comparison of hit/miss analysis to signal response analysis			
Generate data sets using experimental plan from 3.1 and available flat plate samples. Acquire digital data and inspector hit/miss data.	2/07		On hold per FAA contractual direction.
Complete POD assessment using hit/miss and signal analysis approaches.	4/07		On hold per FAA contractual direction.
Provide recommendation for future POD assessments of this method	5/07		On hold per FAA contractual direction.
Subtask 4.3 – Data summation			
Complete data summation for incorporation into the final report.	5/07		On hold per FAA contractual direction.
Task 5: Final Reporting			
Draft final report submitted to FAA	5/07		On hold per FAA contractual direction.
Final report submitted to FAA	6/07		On hold per FAA contractual direction.

Risk Assessment

The following risk items and applicable mitigation plans have been identified:

Entry Date	Risk Item	Impact	Mitigation Plan	Status	Closure Date
Jul 2004	Acquisition of disk materials for use in fabrication of samples for hcf testing	Delay in sample fabrication and testing could lead to overall delay in the program	All three OEMs will search for applicable components for use in the program and the most suitable and timely part will be selected	6/05 – Several acceptable forgings have been found for titanium with the options more limited in nickel. Final decisions will be made based on maximizing the number of samples that can be taken from a disk. The selection awaits a final decision on the	

				hcf testing geometry.	
Apr 2004	Sample fabrication and testing can be a time-consuming process, dependent on the availability of materials and facilities	Delay in sample fabrication and testing could lead to overall delay in the program	Protocols will be developed to enable testing and characterization at multiple locations	6/05 – Materials for the lcf and localized damage samples has been identified and sample fabrication is on schedule.	Jun 2005
Apr 2004	Thermal acoustics is a new method with no standard procedures or equipment system descriptions in place	Relevancy of data to practical implementation of the method.	Round robin testing is planned which will use equipment set-ups at each of the organizations and should yield a common testing protocol		
Apr 2004	Subcontracts and coordinated research agreement	There could be a delay in start of the technical program while subcontracts and the coordinated research agreement are being put in place.	ETC members have agreed to begin discussion of the CRA prior to actual receipt of the award from FAA to ISU.	1/05 – Subcontracts were not in place until Dec 04 which lead to initial delays. Efforts are underway to compensate for the slow start.	Feb 2005
Feb 2005	Resolution of IP issues associated with the thermal acoustic method.	Potential exists to stifle research in this technology area because of restrictive IP policies at WSU.	Request FAA guidance regarding the Authorization and Consent clause which is part of the ISU prime contract and applicable to this delivery order.	3/05 – FAA provides guidance that the conditions of 3.5-1 Authorization and Consent (April 1996), and 3.5-1 Authorization and Consent, Alternate I (April 1996), are applicable to the TAS program and licensing arrangements with WSU are not necessary to perform this contract.	Mar 11, 2005

Entry Date	Risk Item	Impact	Mitigation Plan	Status	Closure Date
Jun 2005	FAA requests discussion with WSU regarding use of their patented technology. Potential exists that WSU/Siemens will pursue legal action against the federal government which would necessarily lead to federal expenses to address the claims.	Potential schedule and program delays as well as a stifling impact to widespread use of the technology.	Request information from Siemens regarding their intentions.	6/05 – Meeting held with Siemens to discuss their position. Request made to have written documentation of their position.	

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