The E-Drill Story

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E-Drill is a New Approach to an Outdated Process

E-Drill

Fastener Separation Technology

- E-Drill is a first-of-kind technology designed to remove the hardest aerospace fasteners 10-20X faster than conventional drilling methods
- Patented electro discharge machining (EDM) technology is used to machine hard metals such as titanium, steel and nickel alloys in “seconds” rather than “minutes”
- Substantially reduces cost, damage, time, FOD, and repetitive motion injuries

E-Drill: How It Works

E-Drill is like a plunge EDM system

The hand-held tool is aligned to the fastener

An electrode machines through the head/tail of installed fasteners using powerful proprietary spark erosion process

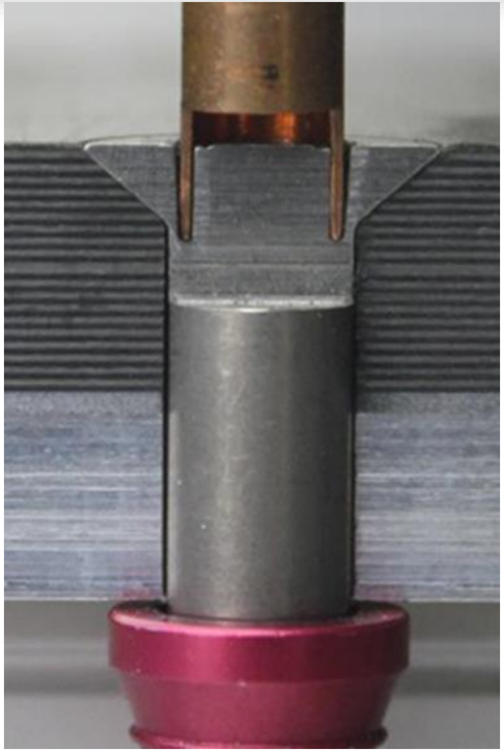
Cut area is continuously quenched by high-flow water bath

Electrode cuts to pre-programmed depth specific to fastener

Remaining fastener is removed by punching action

When used correctly the cutting electrode and EDM process remains inside the fastener shank and no-damage is produced

If misaligned to the fastener, EDM damage could be produced on the aircraft skin



Why Is E-Drill Not Approved For Use?

Initially launched in 2009

- E-Drill was met with significant market interest
- Time-Savings, Cost Savings, and FOD/Injury Reductions drove early market adoption
- US DoD, OEM's, Military and Commercial MRO Service Providers began fielding E-Drill
- A team of connected sales reps and distributors began to push the tool onto the market

HOWEVER….

- Several fundamental design features were not stable and had a potential of damaging structure
- The EDM process could damage/degrade metallic material properties if mis-located
- E-Drill had not gone through an extensive material evaluation and its potential after-effects were not readily understood.

What Could Go Wrong?

A Premature Launch

In 2012 the A-10 program evaluated E-Drill for use on fly-away parts and discovered several critical issues with fielding this untested technology.

In 2014 the F-18 program conducted a similar research project and again found issues.

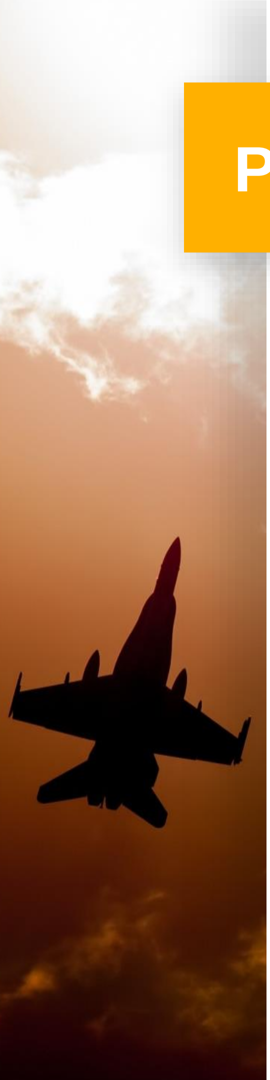
<u>Key Issues</u>

- Locational Accuracy
- Damage Identification
- Damage Repair
- User Training/Certification
- Product Sustainment/Integration

"In conclusion, the E-Drill tool shows promise to be a useful tool for maintenance activities, however, if used near structure that will continue to be placed in service, ***<u>significant understanding</u> and potential <u>tool development</u> must be pursued***. Processes may be developed along with training and certification of users to reduce the probability of damage to a negligible level. However, the possibility of damage from the E-Drill still exists. It is likely that oversize requirements could be developed to remove all of the E-Drill compromised material to a 95/95 or potentially higher level of reliability. Finally, based on the discoveries of this study, use of the E-Drill tool for A-10 lower wing skin maintenance is not recommended at this time; specifically, the use of the E-Drill for removal of fasteners with the fastener head in aircraft structural parts indicated as flight critical and for re-use, is not recommended. Use of the E-Drill for removal of structural parts designated to be replaced by new parts was not addressed and is likely still worth consideration."

A-10 SPO Evaluation of E-Drill- (2012)
Reference Report # SWRI-12-16364-10-1
Closing Statement, PG. 42

E-Drill Was Not Ready



Product Improvements

The A-10 evaluation noted the possible benefit to the E-Drill but saw two areas that needed to be addressed:

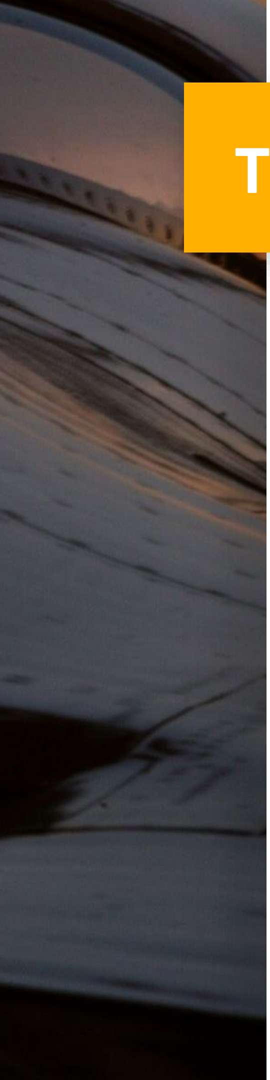
Significant Understanding
And
Potential Tool Development

At the time, Perfect Point could only address one - *Make their product better*

Perfect Point organically funded and developed incremental system improvements and produced a more accurate and reliable version of E-Drill

Product Improvements

Depth Control
→ Higher Fidelity Control System(s)
Locational Accuracy
→ Better Point-to-Interface Tooling
Over-Heating Potential
→ Higher Volume Water and Vacuum
Cut Site Breakout
→ New Alloy Electrodes



Top Level Improvement Matrix

Failure Mode	Outcome	Severity	Root Cause	Corrective Action
Inconsistency of Cut Depth	Damage to skin	Extreme	Command Maturity, Control System Resolution/Accuracy	Improved PCB Control Card, Designed and Produced an Advanced Power Control Function, Defined Best Programming Practices Based on Fastener Datasheets, Introduced Field Customizable Programming
Excessive Burning At Cut Location	Damage to skin	Extreme	Electrode Kerf Boundary, Grounding Pin Erosion and Water Flow	Changed Electrode Alloy, Refined Grounding Pin Design, Higher Efficiency Fluid System
Inconsistency of Cut Placement	Damage to skin	Extreme	Point of use locating tools highly uncontrollable	Designed, Tested, Fielded Improved Alignment Tooling Product Lines, Introduced Mechanical Indexing Features and High Resolution Optical Alignment Devices
High Failure Rate of Tool	Damage to tool	Critical	Water Leakage Damaging Hand tool Controls	Refined Seal and Bearing Designs, Sourced Better Materials for Umbilical and Strain Relief, Refined and Improved Manufacturing Practices
Tooling Configuration Complexity	General damage	Critical	Inconsistent tooling set ups, based on operator familiarity with system	Developed kitted tooling solutions based on work being performed, including all tooling required for successful precision outcomes.

Time to Relaunch

In 2017 Perfect Point relaunched E-Drill in-earnest

While the Product Improvements made the tool more accurate and easier to use, the market needed proof that the system was indeed “aerospace” grade.

Perfect Point partnered with the Prime OEMs and other customers to put E-Drill through trial evaluations and proved the benefits of our improved technology.

Since 2019, E-Drill has made strides to become the fastener removal system of-choice for the market.

Perfect Point’s E-Drill was named Best New Product in the Defense Category

Moving Forward

Several proprietary evaluation studies were performed by various customers, but nothing public has been released since the A-10 Evaluation of E-Drill in 2012 and F-18 Evaluation in 2014.

For the U.S. DoD, the material question(s) remained unanswered- Is the fastener being “super-heated” during the cut? What happens if E-Drill accidentally damages a skin? Can it be identified and/or repaired?

In 2018 Perfect Point performed a small-scale Proof of Concept study that showed promising results but did not have the statistically relevant sample sizes to draw definitive conclusions

In 2020 Perfect Point partnered with the US Air Force Rapid Sustainment Office to commission a study of the after-effects of potential E-Drill Damage.

<u>Significant Understanding</u>- Must Be Pursued

General Background: EDM Basics

Electro Discharge Machining (EDM) – The Science

- Electro Discharge Machining (EDM) is a machining method primarily used for hard metals that are very difficult to machine with traditional techniques.
- EDM easily machines through the hardest alloys such as: hardened steel, titanium, Monel, Inconel, etc.
- EDM processes materials by arcing DC current through an electrode to the work-piece which spark-erodes small amounts of material until the desired cut profile is completed.
- During the machining process a di-electric liquid bath is required to maintain the sparking process

EDM Side Effects

- Recast –the area around the cut is in a molten state that recrystallizes creating a recast layer that can affect the metallurgy
- Heat Affect Zone (HAZ) is also present around the EDM area that may affect the metallurgical properties
- Micro-cracking can appear inside the HAZ and Recast layer(s) which degrades structural integrity

General Background: E-Drill Basics

E-Drill Removal Process

- E-Drill locates on fastener head and machines inside the fastener body to ensure no EDM by-products interact with the surrounding hole, skin, or substructure
- Hi-resolution depth-control prevents EDM escaping under the fastener head
- Short cut times and continuous flushing/vacuuming prevent heat from building up
- EDM by-products remain internal to the subject fastener, which is then removed and scrapped
- Process is typically 10-20x faster than traditional methods

Risks

- Mislocating the tool can cause a small EDM strike on the hole
- Like drill damage, an EDM strike can introduce damage to the base material- micro-cracking and microstructural

Mitigation

- Damage is easily identifiable
- Standard over-size reaming removes the affected area

But…Where is the Proof

Anecdotally the technology has improved over the years, but no publicly-available exhaustive body of work has been produced since 2012.

Perfect Point has partnered with several large organizations to perform proprietary testing but never owned the data produced.

As part of the U.S. Air Force 20.1 Phase 2 SBIR, Perfect Point developed a set of controlled experiments designed to prove the efficacy of their EDM technology.

Evidence Based Material Research

Primary Research Questions

1. When Used Correctly- Does E-Drill Cause Damage?

Question(s) = Does the fastener get hot enough to damage the hole/skin, when cut on-center? Does E-Drill leave any deleterious artifacts on skin/hole surface, if fastener is cut on-center?

Test= Interrogate a fastener and hole during/after a centered and off-set cuts.

Method= Hi-Speed/Resolution Thermal Imaging, Micrographic analysis, Fatigue

2. When Used Incorrectly- Does E-Drill Cause Damage?

Question=What happens if E-Drill hits the skin?

Test= Intentionally Offset the tool and Characterize the damage

Method= Micrographic Analysis

3. Can E-Drill Damage Be Repaired?

Question= What do we do after an EDM Strike?

Test= Rectify EDM damage by reaming

Determine amount of degraded material that needs to be removed based on dimensions of EDM Strike

Method= Micrographic Analysis and Fatigue Life Testing

Infrared Thermal Imaging

Objectives

- Determine heat profile of EDM process related to location of cut
- Compare temperatures for E-Drill processed fasteners against conventionally accepted removal methods.

Method

- Record temperature profiles of E-Drill cuts (sample locations on skin and fastener)
- Progressively offset EDM cut site closer to breakout boundary of fastener
- Record temperature profiles of hand-drilled fastener removals (same sampling)
- Compare results

Infrared Thermal Imaging: Test Setup

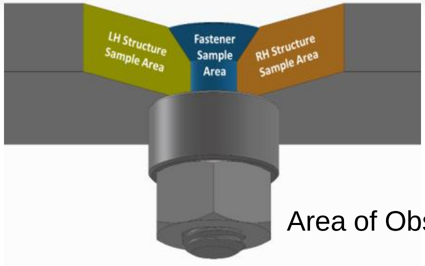
Perfect Point contracted with a FLIR Science Segmentation Engineer to record and compile raw data.

Camera Recording Details- 1000 FPS, 0.003” pixel resolution, ~40°F-700°F recording range.

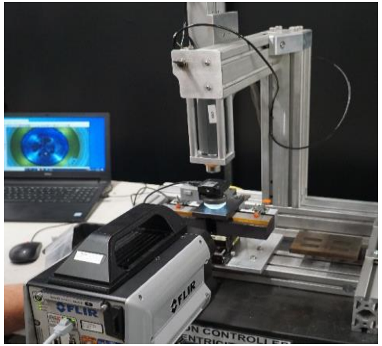
Fasteners Tested- HL13V-8 and HL21PB-8
Base Material- Al 7075-T6
Radial Offset Conditions Tested –
E-Drill: Breakout (0.014”), 0.013 - 0.010”
0.000”(Centered)
Hand Drill: On-center
Replicates- 5(ea.) Condition

Coupon Processing was witnessed by local NAVAIR Materials Engineer to ensure objectivity

FLIR SME compiled the data→ PPEDM interpreted the data



Area of Observation



Thermal Camera Setup

E-Drill Data Collection

A Hi-Lok style fastener was installed into the sample plate and processed with E-Drill according to the DOE.

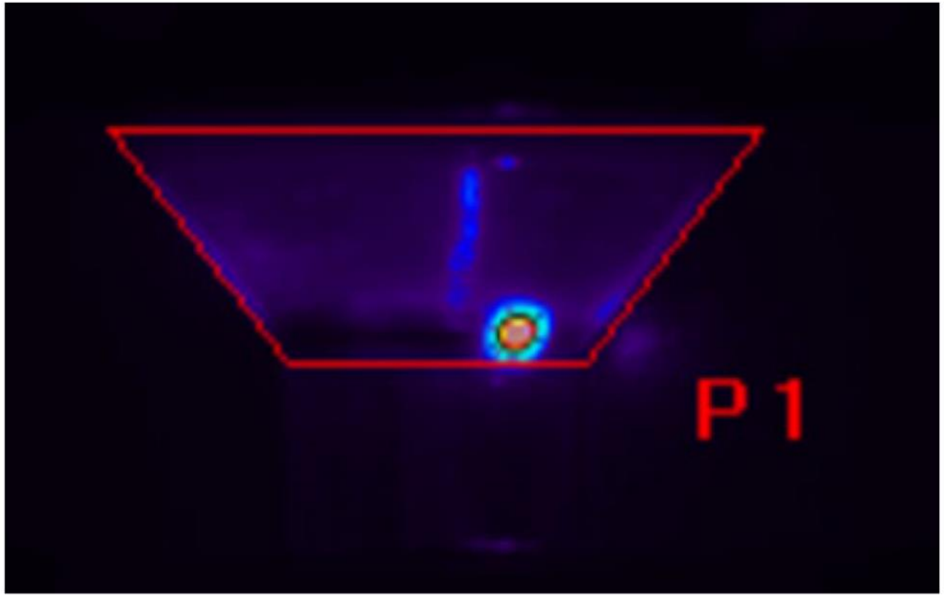
E-Drill test points began at the extreme offset and walked-back towards centerline, in increments of 0.001”.

Heavy focus was put on the structure immediately adjacent to the fastener

Electrode breakout occurred at 0.014” of radial offset and water leakage/ EDM ejecta obscured camera.

Maximum offset was benchmarked at 0.013”. No significant rise in heat was detected on skin around the fastener.

Fastener internal temperature averages had momentary (0.004 – 0.010 seconds) incursions approaching +500ºF.”.



Typical Visualization of Heat Profile at Maximum Radial Offset (0.013”)

Hand-Drill Data Collection

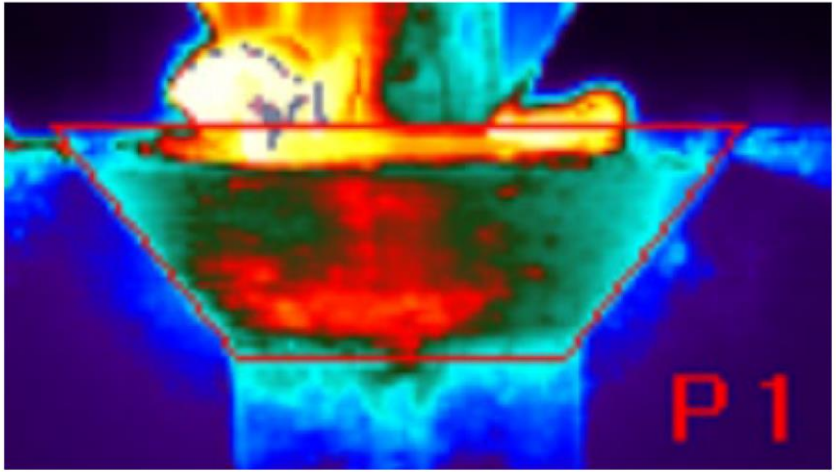
A Hi-Lok style fastener was installed into a sample plate and processed with a hand-drill according to the appropriate TCTO.

Best shop practices were observed (e.g., drill motor RPM, drill bit size/type, lubrication, etc.) and witnessed by a NAVAIR Engineer.

There was no significant rise in heat detected on skin around fastener.

Fastener internal temperature averages had short (0.25-0.35 seconds) incursions approaching +500ºF.

Direct fastener temperature results were comparable to temperatures observed using the E-Drill, however, they existed for much longer durations.



Typical Visualization of Heat Profile (Hand-Drill: On-center)

Infrared Thermal Imaging: Results

There was no significant amount of heat (Δ = <100°F rise) transmitted into the coupon structure by E-Drill or Hand-Drilling.

At 0.013” radial offset, a ~0.001” ligament remained between cutting electrode and fastener side-wall.

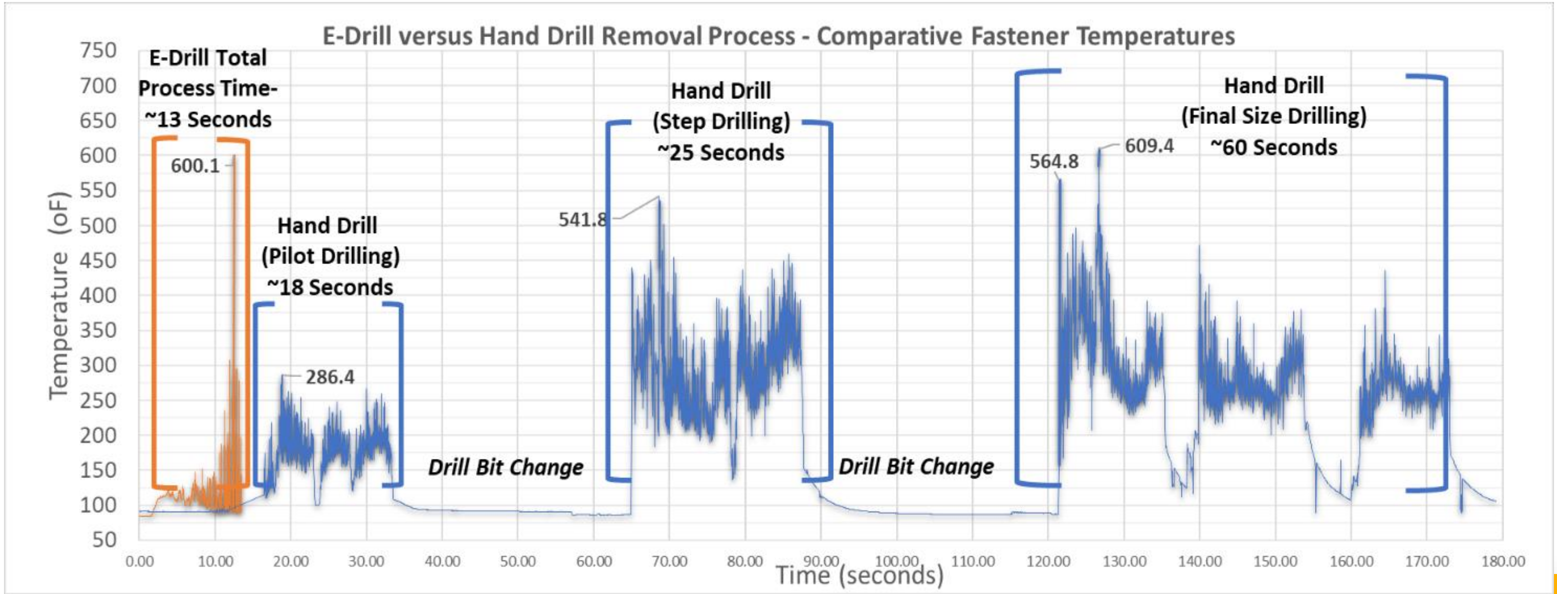
E-Drill temperatures recorded at extreme-offset conditions were comparable to temperatures recorded for Hand-Drilling using best practices.

As EDM process moved away from fastener’s side-wall temperatures decreased.

Hand-drilling remained constant throughout.

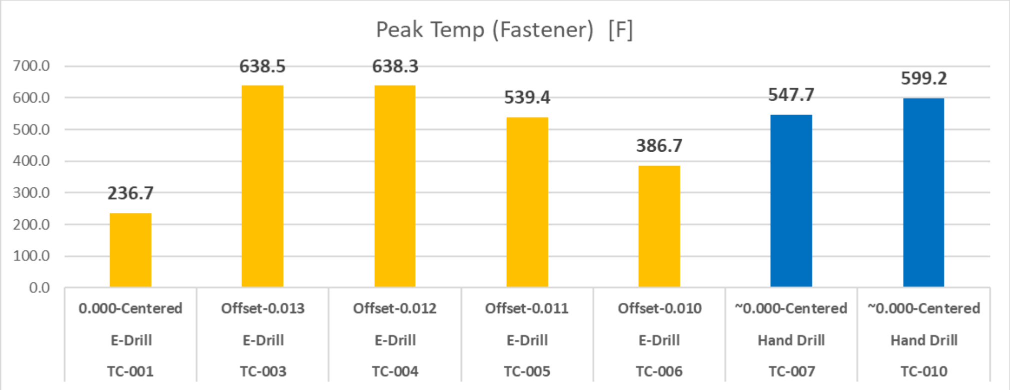
Infrared Thermal Imaging: Results

0.013” Offset E-Drill vs. Hand-Drill

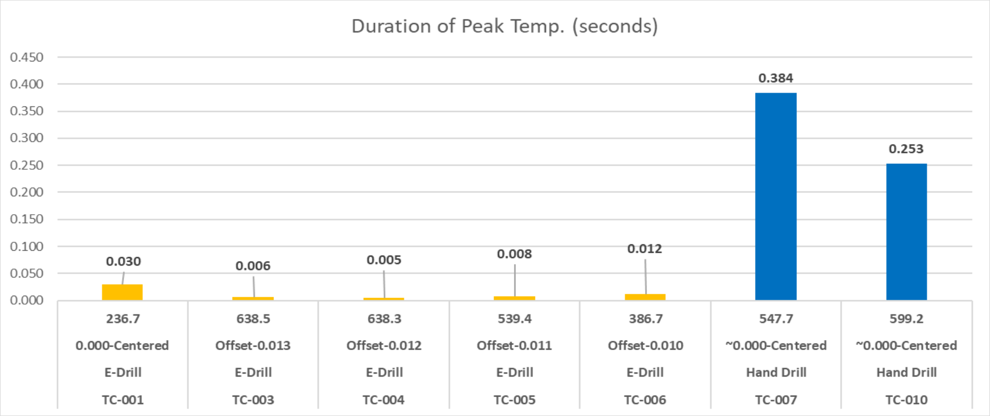


E-Drill produced comparable heat profile, but for significantly less time.

Infrared Thermal Imaging: Results



Average temperatures and durations for each test condition (5 replicates- each test point)



Infrared Thermal Imaging: Results

Heat transmitted by E-Drill to the fastener had a direct functional relationship to the degree of offsetting and only peaked near the end of the cut cycle when the electrode has nearly reached the desired cutting depth.

Heat transmitted by Hand-Drilling has a direct functional relationship to the diameter of the cutter and the downward force used during the cutting process; and existed throughout the whole cutting process.

Instantaneous temperature values produced by E-Drill at maximum offsetting were comparable to the temperatures experienced by currently acceptable hand-drilling processes.

During peak intensity, E-Drill temperature values exist for >10X less time than currently accepted Hand-Drilling values.

E-Drill coupon processing was a short, controlled, and secure method producing no coupon deflection/vibration or debris in the test observation area, whereas Hand-Drilling was a longer and more disruptive method producing significant amounts of debris and coupon deflection/vibration in the observation area.

Infrared Thermal Imaging: Conclusion

Based on the research*, it can be stated:

E-Drill cuts with-

A radial offset <0.013” does not heat the fastener to a degree greater than traditionally accepted practices (Hand-Drilling).

A radial offset >0.013” causes an energetic electrothermal event that exits the fastener and can not be quantified further with Infrared Thermal Imaging.

Another form of scientific evaluation is required to quantify the after-affects of the breech condition.

**(Reference: 1)*

Micrographic Analysis: Testing

Objectives

- Identify damage caused by EDM strike
- Quantify amount of material required to remove all EDM by-product

Method

- Perform radially offset cuts to determine boundary where damage occurs
- Section holes for micrographic analysis to quantify damage induced at each offset
- Rectify holes per standard repair dispositions
- Submit rectified holes for micrographic analysis to determine if damage has been removed.

Micrographic Analysis: Test Setup

Sample 7075 T6 Aluminum coupons were prepared with standard nominal hole configuration IAW AF TCTO 1-1A-08. HL11V6 fasteners were installed and torqued to manufacturers specification.

(HL11V series fasteners were selected because they are a series of fastener with minimal margin for error and size 6 is the most common size PPEDM has seen during field work)

EDM Damage Evaluation-

- 3 sets of 3 fasteners were subjected to intentional offset cuts. Each offset cut (3 each) was precision placed at 0.012”, 0.015”, and 0.021”
  (*Offsets chosen based off previous micrographic analysis of similar base material/fastener diameter combinations)**

- The three sets of 3 fasteners were sectioned through the EDM offset cut, mounted, polished and etched. Using optical microscopy, the EDM artifacts were characterized and quantified.

EDM Repair Evaluation-

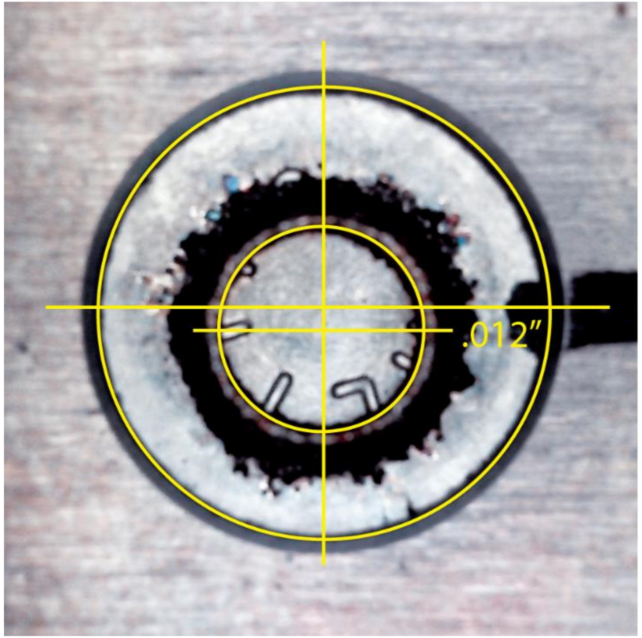
- 1 additional set of fasteners with the same offset cuts was rectified as required to the standard rectification of 1st or 2nd oversize hole specification.

- The set of 3 rectified fasteners were sectioned through the EDM offset cut area, mounted, polished and etched to detect if any EDM artifacts remain.

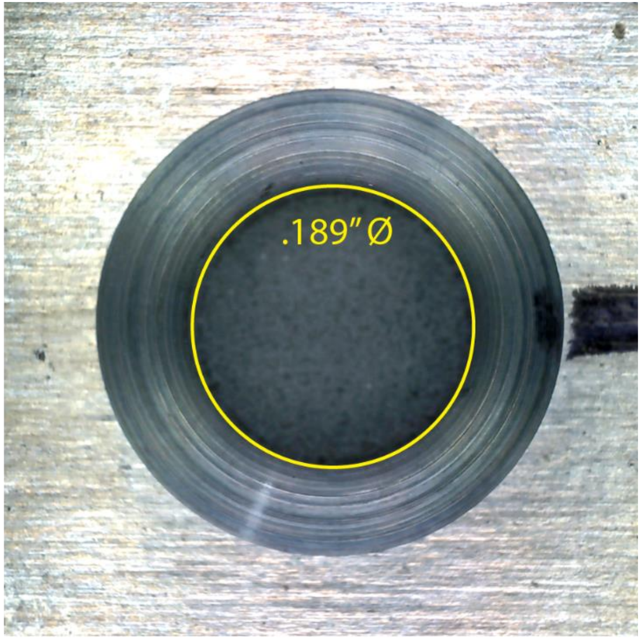
(Reference: 2)

Micrographic Analysis: 0.012” Offset EDM Cut

HL11V6 (Shear Head)

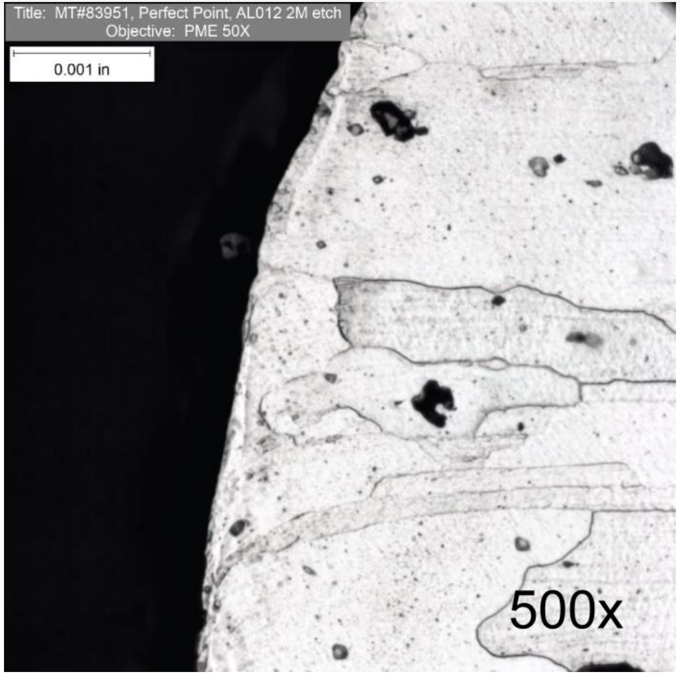


Offset Condition on Fastener Head



No Damage to Hole, No Rectification

Micrographic Analysis: 0.012” Offset EDM Cut



EDM Sample-0.012” Radial Offset
No Damage to Hole
(Keller’s Etch)

EDM Sample-0.012”
No Rectification Performed/Required

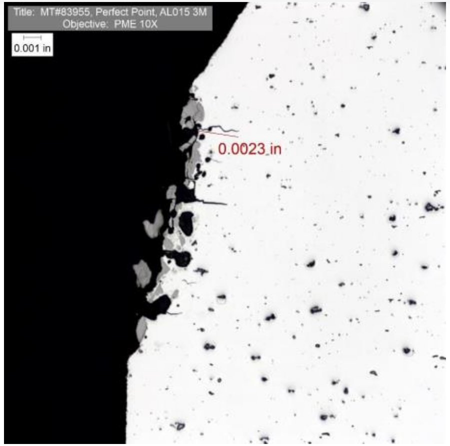
Micrographic Analysis: 0.015” Offset EDM Cut

HL11V6 (Shear Head)

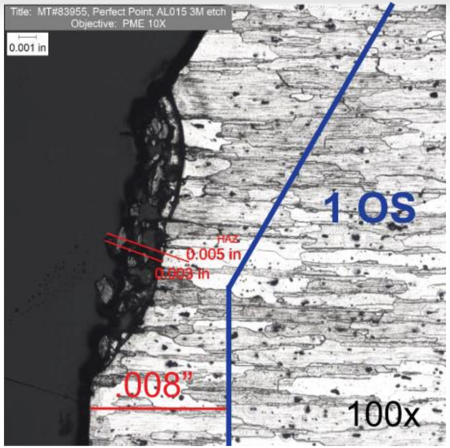
Offset Condition on Fastener Head

Hole Damage Indicates 1st OS Repair

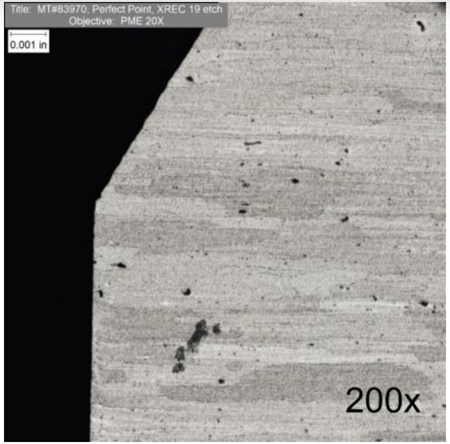
Micrographic Analysis: 0.015” Offset EDM Cut



EDM Sample-0.015”
Radial Offset
Minor Damage to Hole
(Un-etched)



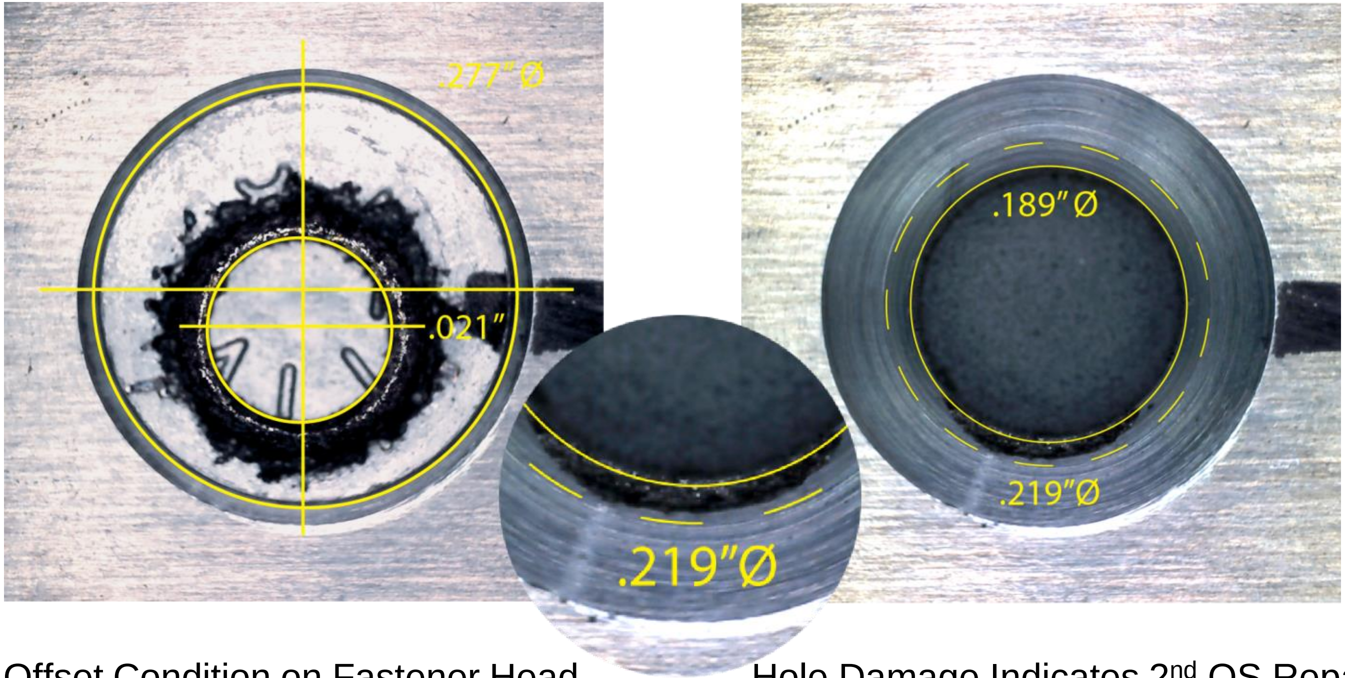
EDM Sample-0.015”
Radial Offset
Minor Damage to Hole
(Keller’s Etch)



EDM Sample-0.015”
Offset Rectification
1st Oversize (0.203”)
Removed All Damaged
Material

Micrographic Analysis: 0.021" Offset EDM Cut

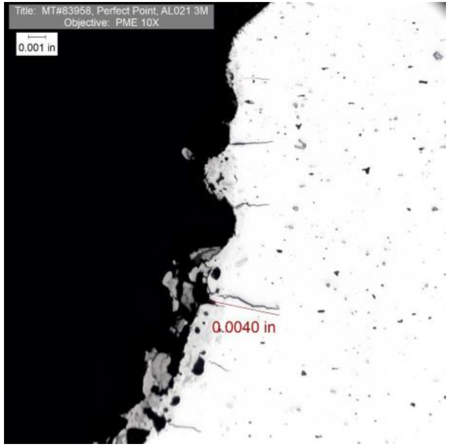
HL11V6 (Shear Head)



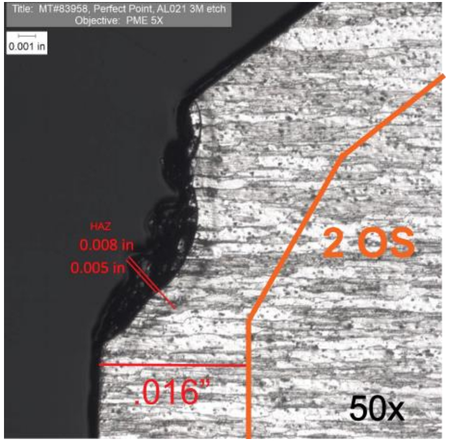
Offset Condition on Fastener Head

Hole Damage Indicates 2nd OS Repair

Micrographic Analysis: 0.021” Offset EDM Cut



EDM Sample-0.021”
Radial Offset
Moderate Damage to Hole
(Un-Etched)



EDM Sample-0.021”
Radial Offset
Moderate Damage to Hole
(Keller’s Etch)

EDM Sample-0.021”
Offset Rectification
2^{nd} Oversize (0.219”)
Removed All Damaged
Material

Micrographic Analysis: Conclusion

Based on the research*, it can be stated

For an HL11V-* Fastener installed in AL7075-T6 Skin -

- *Radial offsets <0.013" do not interact with the base material (hole, csk, skin, etc.)*
- *Radial offsets between 0.013-0.015" cause minor damage to the csk/hole, which can be removed by 1st OS Reaming Process*
- *Radial offsets between 0.016-0.021" cause moderate damage to the csk/hole, which can be removed by 2nd OS Reaming Process*

- Radial offsets >0.021" were not tested, but evidence suggests that it is repairable.
- Other fastener/skin combinations were not tested but evidence suggests results would be comparable.

To further validate these findings, Fatigue Life Testing was performed using these values.

**(References: 2-4)*

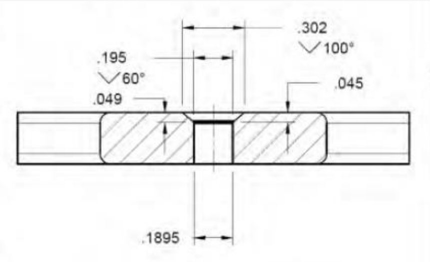
Fatigue Life Testing

Objectives

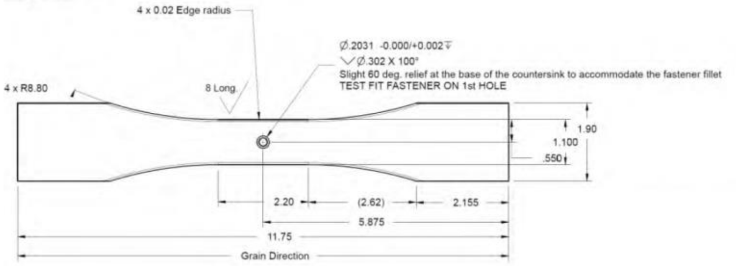
- To determine if rectified E-drill damaged holes have any greater Knock-Down than baseline holes of the same diameter
- To determine whether Fatigue Life Performance support Microstructure results
- To confirm rectification required in aluminum structure for degree of damage incurred

Test

- Conduct offset fastener cuts per DOE
- Test samples against baseline holes of same diameter



Fatigue Coupon Dimensions



Fatigue Life Testing: Test Setup

AFRL Primary POC Defined Test Values-

3 stress cycle target bands (25K, 100K, 250K Cycles)
Reverse Loading value = -0.1
Replicates- 6 ea.
Process per ASTM E466

Material- AL 7075-T6
Fastener- HL11V-6
Replicates- 6 (ea.) Condition (108 total)

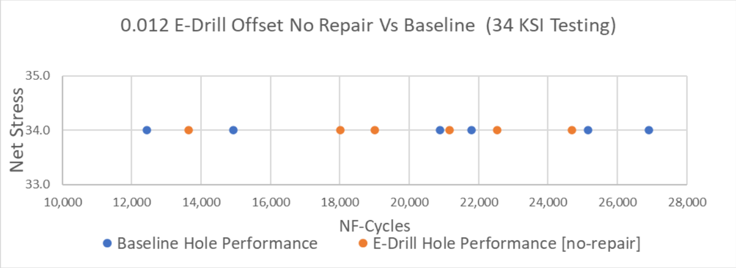
Perfect Point contracted with a METCUT LABS for compliant DOE. 3 stress loads chosen (34, 28, 26 KSI) derived from sample testing to reach Customer Defined requirement for cycles*

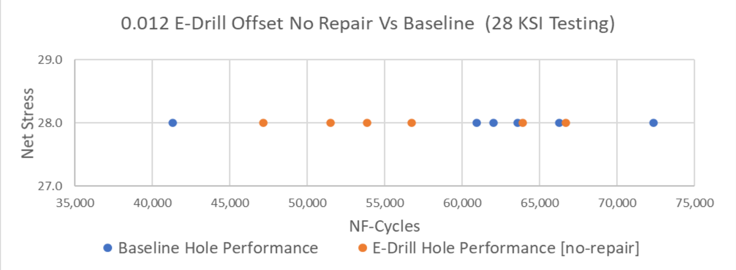
MetCut Designed and fabricated coupons
Hole dimensions were IAW AF TCTO 01-1A-08
Installed Fasteners per TCTO and MFG Instructions

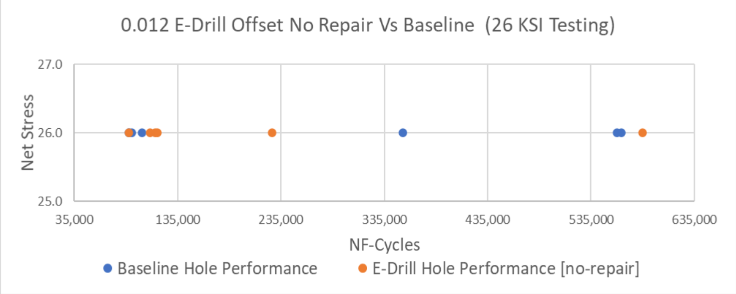
Perfect Point processed E-Drill samples at same offsets as micrographic analysis (0.012”, 0.015”, 0.021”) and returned coupons to MetCut for disassembly, repair (if-required by DOE), and test processing.

**(Reference: 5)*

Fatigue Life Testing- Baseline Performance







<u>Test Conditions</u>

Hole Diameter= 0.189” (Both)

E-Drill Radial Offset= 0.012”

No Post-EDM Rectification or Hole Cleanup

6 Samples Ea. (Baseline and E-Drill)

Tested at 34, 28 and 26 KSI
R= 0.1

Cycles for 3 stress levels plotted

Crack Initiation Sites from 0.012” Offset Testing

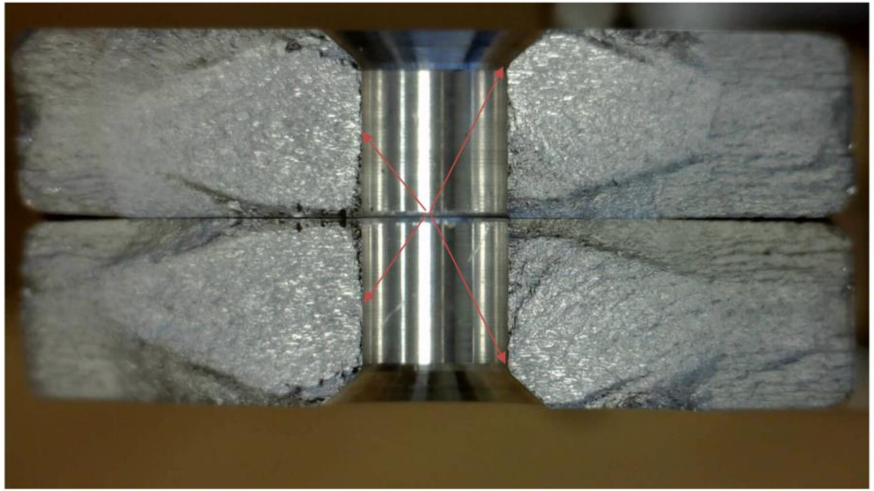


Figure 5: Specimen NB-9; S, L, H / S, R, CSK failure mode

Baseline Sample- 3/16” CSK Hole
Crack initiation at counterbore of CSK
(Red Arrow=Crack Initiation Site)

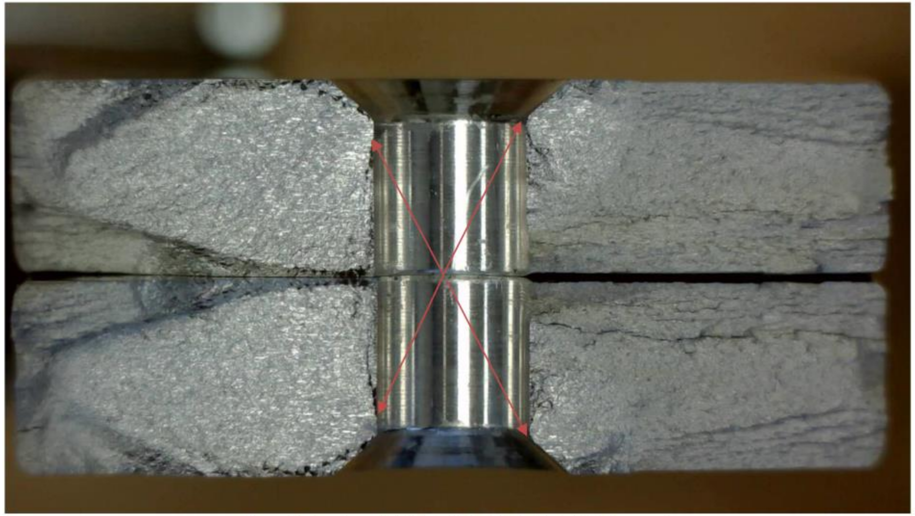
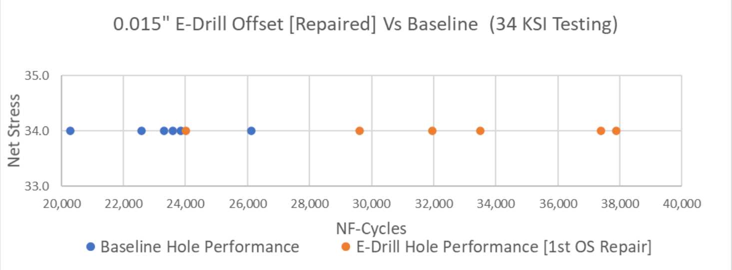
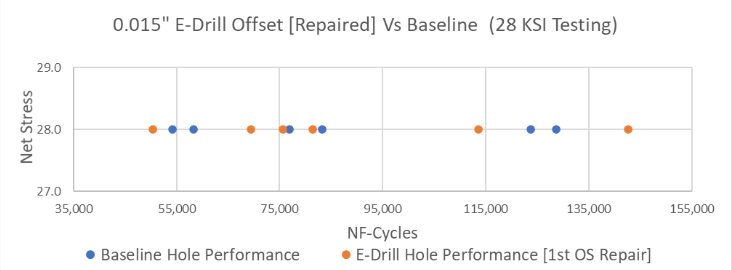


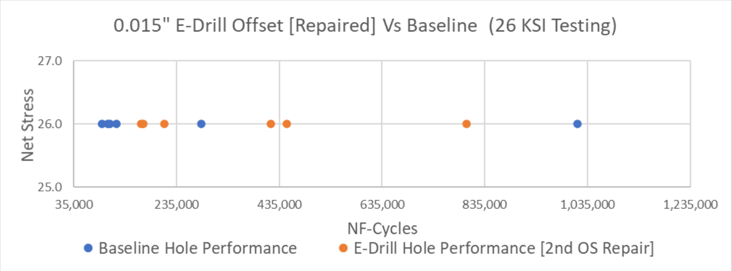
Figure 6: Specimen ECNR-8; S, L, H / S, R, CSK failure mode

E-Drill Offset (0.012”) Sample- 3/16” CSK Hole [No-Repair]
Crack initiation at counterbore of CSK.
(Red Arrow=Crack Initiation Site)

Fatigue Life Testing- 1st Oversize Performance







Test Conditions

Hole Diameter= 0.203” (Both)

E-Drill Radial Offset= 0.015”

E-Drill samples original hole diameter reamed to 1st oversize (0.203”)

6 Samples Ea. (Baseline and E-Drill)
Tested at 34, 28 and 26 KSI
R= 0.1

Cycles for 3 stress levels plotted

Crack Initiation Sites from 0.015” Offset Testing [1st Oversize Repair Validation]

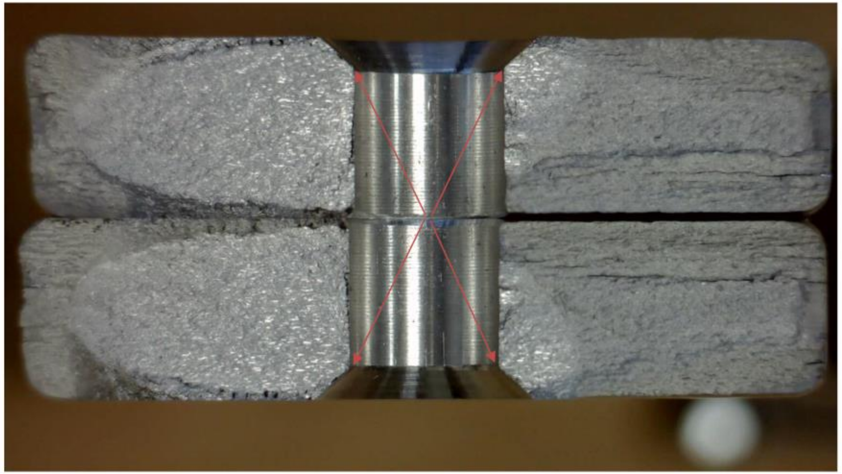


Figure 8: Specimen BX-7; S, B, CSK failure mode

Baseline (Non-E-Drill) Sample- 0.203” CSK Hole
Crack initiation at counterbore of CSK.
(Red Arrow=Crack Initiation Site)

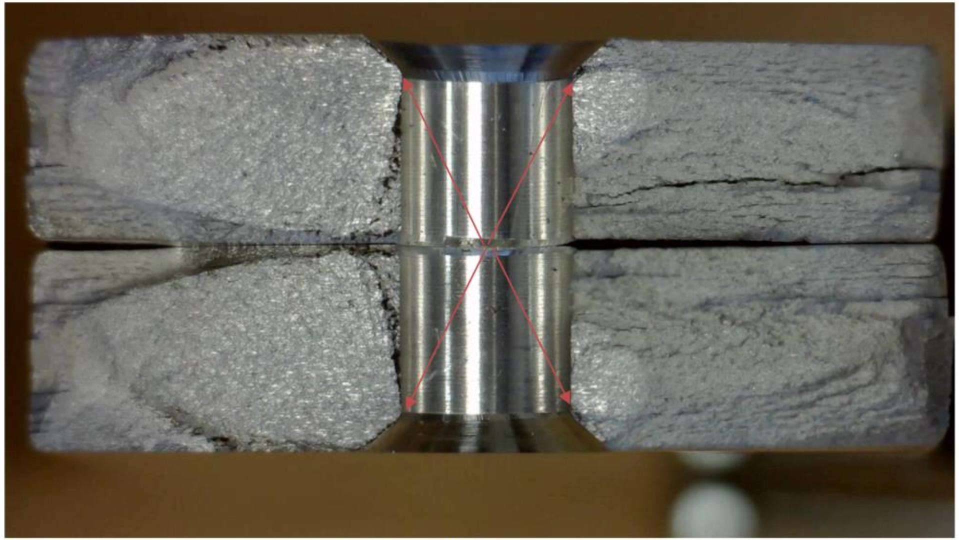
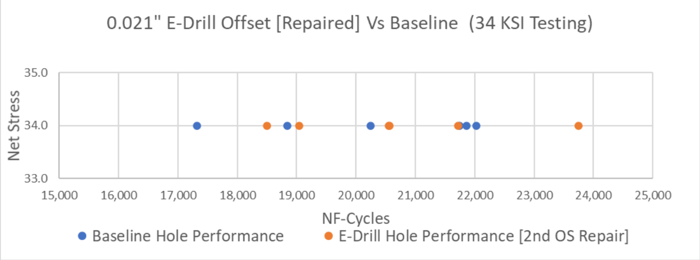
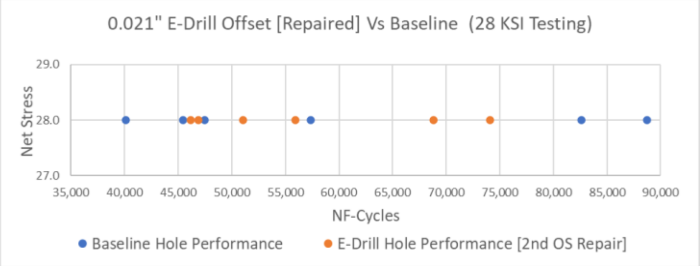


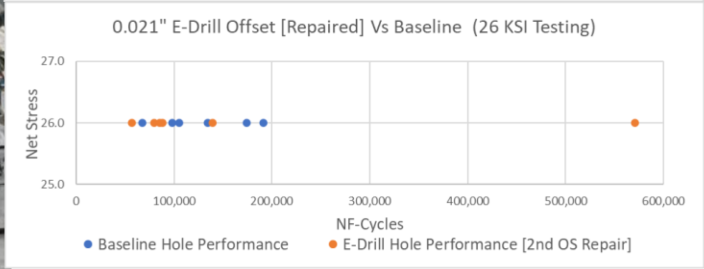
Figure 10: Specimen XREC-7; S, B, CSK, P failure mode

E-Drill Offset (0.015”) Sample- 0.203” CSK Hole [Post-Repair]
Crack initiation at counterbore of CSK.
(Red Arrow=Crack Initiation Site)

Fatigue Life Testing- 2nd Oversize Performance







Test Conditions

Base Hole Diameter= 0.219” (Both)

E-Drill Radial Offset= 0.021”

E-Drill samples original hole diameter reamed to 2^{nd} oversize (0.219”)

6 Samples Ea. (Baseline and E-Drill)
Tested at 34, 28 and 26 KSI
R=-0.1

Average Cycles for 3 stress levels plotted

Crack Initiation Sites from 0.021” Offset Testing [2nd Oversize Repair Validation]

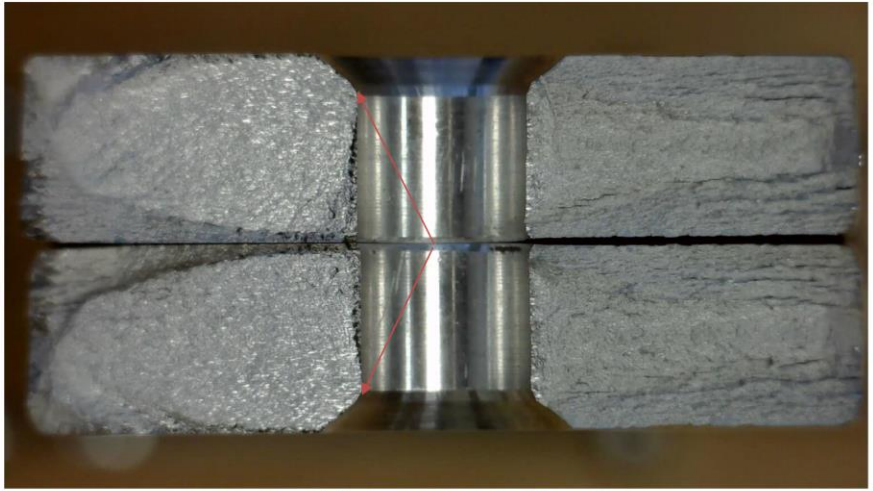


Figure 13: Specimen BY-13; S, L, CSK failure mode

Baseline (Non-E-Drill) Sample- 0.219” CSK Hole
Crack initiation at counterbore of CSK.
(Red Arrow=Crack Initiation Site)

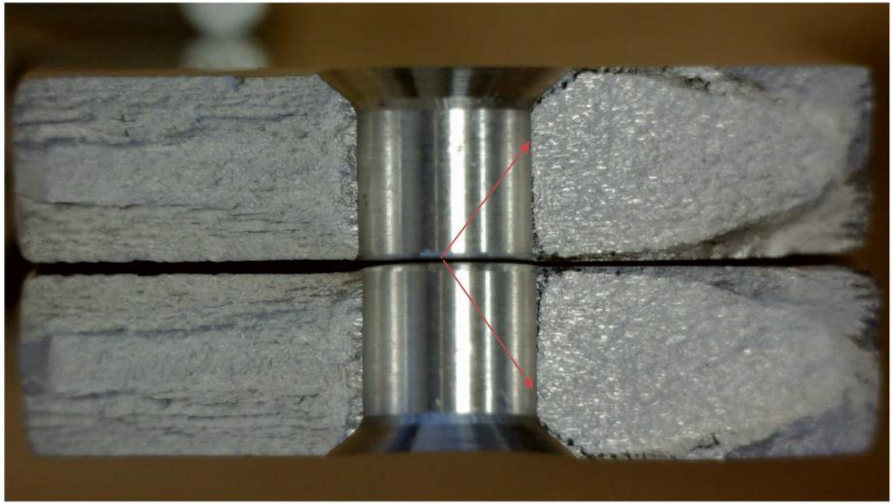


Figure 14: Specimen BY-14; S, R, H failure mode

E-Drill Offset (0.021”) Sample- 0.219” CSK Hole [Post-Repair]
Crack initiation in hole sidewall
(Red Arrow=Crack Initiation Site)

Fatigue Life Testing- Conclusion

Analysis from MetCut Labs determined there was no statistically relevant difference in performance between baseline samples and E-Drill samples*.

Based on the research**, it can be stated

For an HL11V-6-* Fastener installed in 7075-T6 Series AL

- *Radial offsets <0.013" E-Drill cuts do not interact with the base material (hole, csk, skin, etc.)*
- *Radial offsets between 0.013-0.015" cause minor damage to the csk/hole, which can be removed by 1st OS Reaming Process*
- *Radial offsets between 0.016-0.021" cause moderate damage to the csk/hole, which can be removed by 2nd OS Reaming Process*

- Radial offsets >0.021" were not tested, but evidence suggests that it is repairable.

**(Reference 4)*

***(References 4-8)*

Research Conclusions

Research Questions

1. **When Used Correctly- Does E-Drill Cause Damage?**

   No

2. **When Used Incorrectly- Does E-Drill Cause Damage?**

   Yes

3. **Can E-Drill Damage Be Repaired?**

   Yes

A standard repair procedure can remove EDM damage from aluminum.

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(2.) National Technical Systems (2021): Test Report No. PR128708- *[Micrograph Analysis & Microhardness]*

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(3.) MetCut Research Inc. (2021): Test Report No. 6032-106782-1 *[No Title]*

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(4.) *MetCut Research Inc.* (2021): Test Report No. 6032-106782-2 *[No Title]*

Fatigue Testing Report(s)

Fatigue Testing Program

(5.) MetCut Research Inc. (2021): Test Report No. 6032-106551-1 *[SBIR Fatigue Testing Program of Eccentric Cut E-Drilled AL7075-T651 Specimens; No Rectification, X Rectification & Y Rectification]*

Fractography

(6.) MetCut Research Inc. (2021): Test Report No. 6032-106551-2 *[No Title]*

(7.) MetCut Research Inc. (2021): Test Report No. 6032-106551-3 *[No Title]*

(8.) MetCut Research Inc. (2021): Test Report No. 6032-106551-4 *[No Title]*