15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

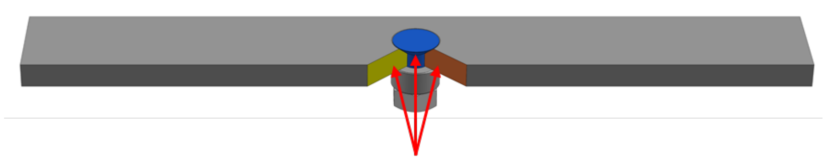
Executive Summary

Perfect Point EDM's E-Drill Fastener Separation Technology (FST) is the world's first portable electro-discharge machining (EDM) system designed to remove fasteners installed in aerostructures. Used correctly, the E-Drill produces a concentric and co-axial cut inside the fastener and does not touch the fastener hole or surrounding skin or substructure. During a cut process the E-Drill uses pulsed DC electricity and high-pressure water to keep the working area cool while machining the subject material.

EDM damage can occur on structure when the E-Drill hand tool is mislocated and the cutting electrode breaches the fastener wall, thereby subjecting the structure to direct EDM. Understanding that potential failure mode, the technical community has repeatably expressed concern regarding the potential of latent thermal damage that could occur if a fastener were processed at the extreme edge of integrity loss. This study only addresses fasteners that were not breached during the EDM cycle.

Perfect Point has studied the after-effects of its unique EDM process and developed a series of controlled experiments to study the thermal properties of a fastener and surrounding structure cut by E-Drill against that of a fastener cut by conventional hand-drilling. The purpose of this experiment was to empirically address the technical question: whether an E-Drill cut that remains inside the subject fastener produces a significantly high enough thermal load to affect the structure in which the fastener is installed. Perfect Point executed this experiment, with the assistance of FLIR Systems and NAVAIR Materials Engineering, to ensure accuracy and objectivity.

Coupons were constructed out of 7075-T6 series aluminum with titanium and steel fasteners installed. E-Drill was used to cut fasteners subjected to precise offsets during processing, and the process was recorded by a high-speed digital thermal camera. The precision offsets were designed to thin the sidewall ligament to within 0.001” from a breech condition and step back in increments of 0.001” in each subsequent test condition. The thermal camera was focused on the fastener and the area directly adjacent to the fastener and recorded the event at high speed.



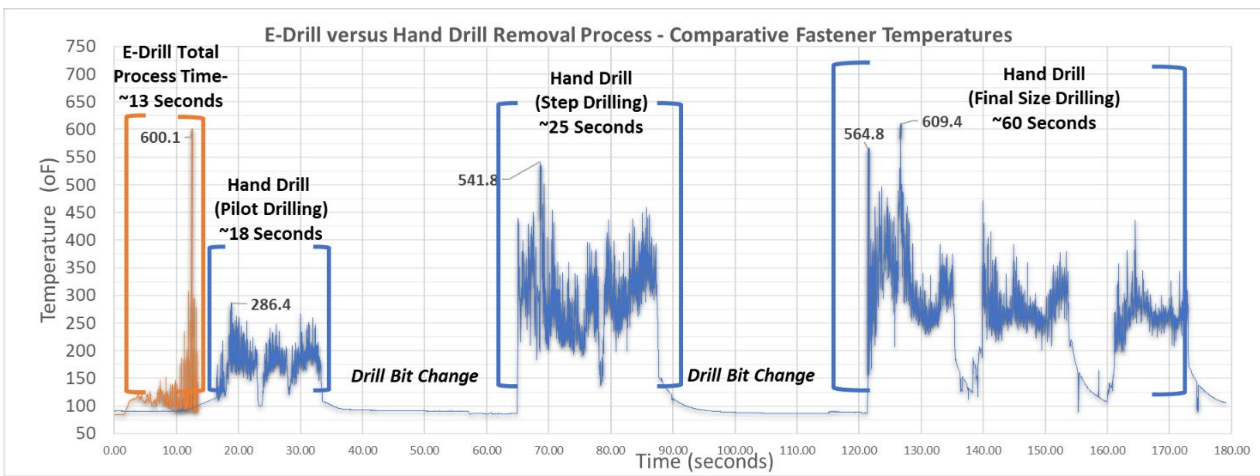
Temperature Sampling Focus Areas

Hand Drilling was used to cut fasteners on-center by following established best technical practices and while no method of precision control was used to ensure concentricity, all fasteners removed with the hand drill method were confirmed to have not damaged the hole. The same thermal sensing methodology was again used to examine the thermal profile of this test condition.

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Throughout the 25 individual tests performed with E-Drill, the highest absolute instantaneous temperature the coupon structure immediately adjacent to the fastener registered was 188°F for a total duration of 0.045 seconds. Relative average absolute temperature peaks recorded on the structure were between 120-150°F. Heated drill shavings falling into the camera's field of view, prevented the continuous measurement of the structure for Hand-Drilled specimens, but random sampling of the 8 individual tests registered approximately 120-180°F throughout the tests. As neither of these temperature ranges are of concern in either metallic or composite structure, the fastener became the subject of further investigation.

Offset E-Drill and On-Center Hand-Drill tests resulted in a similar peak **fastener** temperatures with momentary spikes into the 500-700°F range, however the E-Drill and Hand-Drill processes varied greatly in overall process times and duration of time spent at peak temperatures. Throughout the tests the E-Drill had a consistent average total process time of 10-14 seconds with peak temperatures lasting 0.005-.015 seconds. Hand-Drilling total process times averaged between 120-180 seconds with peak temperatures lasting 0.250-0.375 seconds.



Typical Results of 0.013” Offset E-Drill Compared to On-Centered Hand-Drill

On-Centered E-Drill processing produced average peak fastener temperatures of 220-250°F, which is ~300°F less than peaks observed with on-centered hand-drilling. Considering the overall duration and peak temperatures of both processes, neither process transmitted enough bulk thermal energy to affect metallic or carbon structures.

Analyzing the entire dataset collected from this experiment, it can therefore be concluded that the E-Drill fastener removal process when used correctly, produces no more thermal loading to the fastener or the surrounding structure than the correct use of traditional Hand-Drilling methods. Improper use of either method can cause damage to the structure, and <u>when correctly used the E-Drill process transmits a significantly lower thermal loading and has exponentially better performance time.</u>

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Table of Contents-

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Acknowledgements

Perfect Point EDM would like to thank the following organizations for their technical collaboration and interest during this investigation:

U.S. Air Force: Rapid Sustainment Office

FLIR: Science Systems

NAVAIR: Metals and Ceramics Branch- Patuxent River, MD

U.S. Navy: Fleet Readiness Center Southwest- North Island

The Boeing Company: Research and Technology- Materials and Processes

Lockheed Martin: Enterprise Drilling Technology and Integration

Objective:

To examine the thermal profiles of fasteners and material cut by the E-Drill's Electro-Discharge Machining (EDM) process, as compared to that of fastener removal by conventional hand-drilling. The primary objective of this study shall be to determine the exact thermal properties of a fastener removed by both E-Drill and conventional drilling. This will be accomplished by the use of a high-speed thermal imaging camera, operated by a recognized industry professional.

Test Methodology

Fasteners removed by E-Drill shall be subjected to various off-set conditions designed to iteratively decrease the sidewall thickness between the fastener edge and the cutting electrode. Fasteners removed by traditional methods shall be removed by best-practices as instructed by a credible organization's internal process. Each condition shall be individually repeated so as to generate statistically significant data for independent analysis by prospective adopters of E-Drill.

Test methods and data contained in this report are focused only on the thermal properties of fasteners and material cut by E-Drill, in conditions which the electrode has not breached the integrity of the fastener or material. After-effects of breaching a fastener with EDM shall be investigated through other methods studying the material properties of the structure adjacent to the breach and are outside the scope of this document.

Technology Background:

Perfect Point has developed, the patented E-Drill Fastener Separation Technology (FST) which utilizing electro discharge machining (EDM) technology. EDM is a thermal erosion process designed to precisely remove material from a metallic work piece. The E-Drill uses an electrode to make a circular cut through the fastener head leaving a thin ligament of fastener material connecting the head and the fastener stem which can then be easily removed using a punch. The cutting is accomplished through the use of focused DC electricity pulsed between the cutting electrode and the work piece. Individual sparking events occur around the anulus of the electrode and oblate small amounts of material from the work piece. During this process E-Drill uses deionized water as both a dielectric for the EDM process and as coolant for the work area during the cutting process. The water system flushes the work piece at 80 PSI and evacuates the cut site via a high-flow vacuum system, this process acts as a high-intensity quenching force that keeps the part cool and eliminates FOD.

Similar to all EDM processes, the E-Drill cut results in a thin layer of Recast and Heat Affected Zone (HAZ) that resides inside the cut fastener. Used correctly, the E-Drill makes a concentric and co-axial cut inside the fastener and does not touch the fastener hole or surrounding skin or substructure.

Test Overview:

E-Drill Fastener Removals

7075-T6 series aluminum samples measuring 1" x 8" x .250" were machined for installation of an HL13V8-* and HL21PB8-* fasteners. The samples have a machined "window" allowing for direct thermal imaging of the fastener and the surrounding structure [FIGURE 1A-1B].

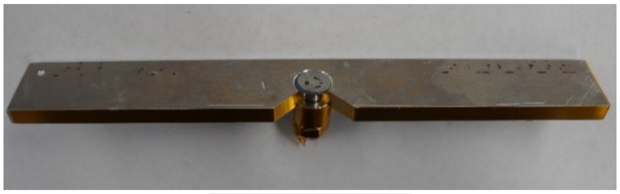


FIGURE 1A

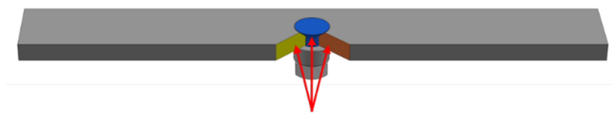


FIGURE 1B

The fastener and coupon assembly are placed into a precision test fixture, with X and Y axis directional control and aligned according to the test matrix (Tables 2-7).

Using fixed controller settings and cutting to a depth of 0.115", a frame mounted E-Drill was used to cut the fastener [FIGURE 2]. Four test points will be collected in every test condition using a titanium HL13V8* fastener, and one test point using an alloy-steel HL21PB8* fastener. The intent of using a small subset of alloy steel fasteners is to study the differences between the alloys when subjected to the E-Drill and Hand-Drill processes.

FIGURE 2: E-Drill Test Fixture

During the E-Drill cutting process, a high-speed thermal imagining device shall document temperatures of the fastener and surrounding structure. A certified thermographer shall operate the recording device and provide objective third-party data interpretation for analysis. This shall ensure scientific objectivity throughout the project and ensure the validity of the data collected.

Each test condition shall be repeated five times to allow for a statistically relevant data set to be created for analysis. This method of data recording shall be used for all test conditions throughout this experiment.

Traditional Fastener Removals

A 0.250" thick plate of 7075-T6 series aluminum was machined for installation of the subject fastener. The sample has a machined "window" allowing for direct thermal imaging of the fastener and the surrounding structure [FIGURE 3]. The sample is mounted to a rigid frame and

FIGURE 3: Rigid Hand-Drill Test Fixture

reinforced with parallel bars to prevent warping of the sample due to downward drill pressure. The subject fastener is then removed with a series of lubricated cobalt drill cutters driven by a low-RPM drill motor, in-accordance-with (IAW) industry best practices.

The removal will be hand-controlled and performed by a certified FAA licensed Airframe & Powerplant (A & P) technician. Drill cutters in this test conditional shall be replaced after every use. Four test points will be collected in every test condition using a titanium HL13V8-* fastener, and one test point using an alloy-steel HL21PB8-* fastener. The intent of using a small subset of alloy steel fasteners is to study the differences between the allows when subjected to the E-Drill process.

Direct Material EDM Cutting

A sheet of 0.125” thick 7075-T6 Aluminum and 6AL4V Titanium shall be used for this test. A handheld vacuum located E-Drill shall be used to cut these sheets to a depth of 0.120”, and a measurement shall be taken from the opposing side. This test condition is designed to study the thermal effects on these materials when the cutting electrode is 0.005” away from exiting the sheet [Figure 4].

FIGURE 4: EDM Cut Test Setup

Reused Drill Cutter Fastener Removal

This test condition will replicate the previous conventionally drilled fastener test, however, in this test condition fasteners will be removed by using the same drill cutters for each test point. The drill cutters of each size in the best condition following the previous drill test shall be used for this test. The subject fastener is removed with a series of reused lubricated cobalt drill cutters driven by a low-RPM drill motor, in-accordance-with (IAW) industry best practices. The removal will be hand-controlled and performed by a certified FAA licensed Airframe & Powerplant (A & P) technician.

Test Preparations:

Prior to testing all fixtures shall be inspected for damage, cleaned, leveled, and squared. All fixture fasteners were inspected, torqued, and replaced as needed. Before any processing coupons and fasteners shall be rinsed with denatured alcohol and allowed to air dry prior to assembly.

Alignment of the E-Drill Fixture and Coupon Fixture will be checked with a digital indicator and is compared to the coupon fixture bore and adjustments made. This will also be verified and documented by use of a digital microscope mounted above the cut location. Overall tolerance of the test fixtures is within ±0.001-0.003"

An additional control is created by the use of a precision ground sleeve mounted to a Vacuum Flush Head Adaptor (VFHL), to ensure concentric alignment of the E-Drill and Coupon Fixture. Finally, an E-Drill mounting cage is affixed to the holding frame and aligned to hold a standard production Center Grounding E-Drill. The coupon fixture assembly is then concentrically aligned to the VFHL and E-Drill assembly.

The thermal imaging device shall be oriented to observe the area of interest and its location relative to the field-of-view shall be documented. The device shall be configured according to the OEM's instructions and all setting shall be documented. [FIGURES 5, 6]

FIGURE 5: Thermal Camera Orientation

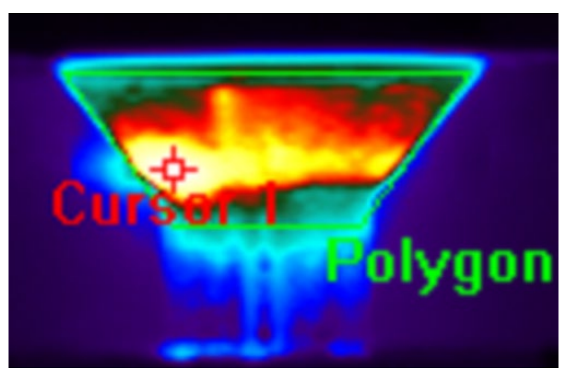


FIGURE 6: Thermal Camera Field of View

Tooling:

Coupon Fixture

A machined offset fixture will used to retain and align the coupons for processing. All test coupons are retained and located by the same fixture in the same manner throughout the process. [FIGURE 7] Two clamps affixed to the fixture hold down the coupon plate during E-Drill cutting to prevent unwanted movement. Both the X-axis and Y-axis are adjustable to allow initial alignment of the test plate to the adaptor block bore. A true machined coupon "gage" is placed in the fixture and the hole location is verified to confirm concentricity.

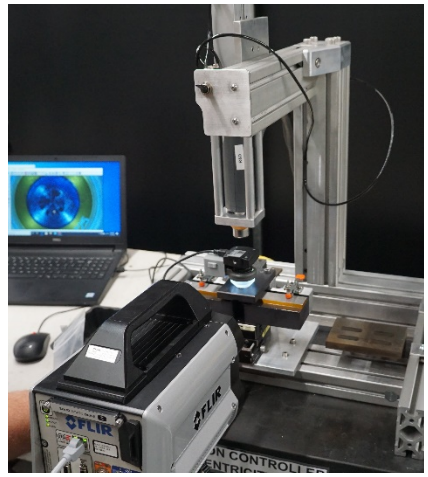


FIGURE 7: Coupon Fixtured in Test Rig

E-Drill Fixture:

An E-Drill fixture is used to ensure repeatability during the cutting cycle of the coupons and to remove any inadvertent operator inputs to the test. A holding cage retains the E-Drill and maintains alignment with the coupon fixture [FIGURE 2]. The cage encapsulates the main body of the E-Drill. The cage was attached directly to the internal E-Drill frame to avoid any misalignment. A guided pneumatic cylinder ensures perpendicularity and that a constant repeatable pressure was applied during the cut.

Thermal Imaging Device:

FLIR™ model X6901sc shall be used to record each test condition. The X6901sc will configured to record at 222 frames-per-second (FPS) and will be calibrated to a temperature range of 50-662°F, with ability to record +/- 10% of the calibrated range. The device shall be setup and operated by a representative of FLIR Systems™ who is a certified expert. Relative location to the sample piece, emissivity, ambient temperature, and humidity shall be recorded for each test condition. Data collected from the device will be collected and interpreted by a laptop computer using FLIR's latest software and will be documented and analyzed by a FLIR Segmentation Engineer.

Test Materials:

Fastener Removal Coupons are produced from 7075-T6 aluminum that was procured through certified vendors. Coupons are machined at Perfect Point EDM to the appropriate dimensions to accommodate this testing.

Direct EDM Cutting Coupons are single sheets of 0.125" thick 7075-T6 Aluminum and 6AL4V Titanium, procured through a certified vendor. No additional machining was required to prepare these coupons.

Hi-Shear™ HL13V8-* [TABLE 1] was selected to be the primary fastener for this trial and was procured through a certified vendor. The HL13V* series fastener is a flush, tension head, titanium Hi-Lok™ fastener that is widely used in aerospace construction. Diameter 8 was selected as a baseline for both E-Drill and conventional removal and is installed into the coupon using representative best practices.

Hi-Shear™ HL21PB8-* [TABLE 1] was selected as the secondary fastener for this test. The intent of using this fastener was to replicate the exact dimensions of the HL13V8-* fastener but substitute the titanium material for alloy steel.

Pin Size Ø	Shank Ø (in)	Head Ø (in)	Head Height (in)	Fillet Radius (in)	Countersink Angle (deg)	Material	Designation
1/4 (Nominal)	.2495 .2490	.5066- .5018	.108 .106	.030 .020	100	Titanium	HL13V8-***
1/4 (Nominal)	.2495 .2490	.5066- .5018	.108 .106	.030 .020	100	Alloy Steel	HL21PB-8-***

Table 1: Fastener Dimensions

Cutting electrodes are produced and provided by Perfect Point EDM with EDK0208-0 being selected as the correct electrode based on the subject fastener diameter.

Solid cobalt drill cutters were procured through certified vendors and will be replaced after each use. Cutter diameters and flute orientation were selected based off of industry best-practices and policies. Cutters will be lubricated with a liquid drill lubricant (Boelube™) frequently during use.

Test Procedures:

E-Drill Fastener Removal:

An assembled coupon is loaded into the holding fixture and clamped taking care that it is firmly in contact with both the side and end stop plates. The holding fixture is adjusted with micrometers to create the desired Y direction offset per Table(s) 2-7. Using the E-Drill configured with a 208-0 (1/4" nominal, copper) electrode, measuring 0.220" in diameter an offset cut is created in the fastener to a depth of 0.115".

Test method:

a. Locate thermal imaging device in correct orientation to the area of interest
b. Place coupon into fixture and using digital indicator ensure concentricity between hole and bushing block
c. Using a 0208-0 electrode and defined depth of cut, with an E-Drill adapter set up in the mounted E-Drill fixture, Adjust fixture to the specified test condition

d. Clamp assembled coupon into fixture against stops
e. Verify coupon placement
f. Begin recording of thermal imaging device
g. Actuate E-Drill Cut
h. E-Drill cut terminates automatically
i. Stop recording on thermal imaging
j. Download image files
k. Record test conditions and observations
l. Repeat per Tables 2-6

Conventional Fastener Removal:

Conventional removal of the fastener was performed IAW best standard practices established for this operation. The test technician shall locate a pilot hole at the center of the fastener and step-drill that hole to the correct diameter for removal. A 500 RPM drill motor shall be used to perform the work and drill cutters shall be lubricated frequently and replaced after each use.

Test method

a. Locate thermal imaging device in correct orientation to the area of interest
b. Install fastener
c. Center-punch fastener
d. Begin recording of thermal imaging device
e. Pilot drill fastener with 0.125” cobalt drill bit
f. Step drill fastener with 0.187” cobalt drill bit
g. Final drill fastener with 0.238” cobalt drill bit
h. Separate fastener via hand-punching
i. Stop recording on thermal imaging
j. Download image files
k. Record conditions
l. Repeat Per Table 7

Direct Material EDM Cutting:

Direct EDM cutting of Aluminum and Titanium sheets was performed by clamping each sheet to a bench mounted vice and aligning the E-Drill to the cut location using Perfect Point’s COTS vacuum locator.

Test method:

a. Clamp coupon into bench-mounted vice
b. Locate thermal imaging device in correct orientation to the area of interest
c. Configure E-Drill with EDK0208-0 electrode and correct command
d. Begin recording of thermal imaging device
e. Actuate E-Drill Cut
f. E-Drill cut terminates automatically
g. Stop recording on thermal imaging
h. Download image files

i. Record test conditions and observations
j. Repeat per Table 8-9

Reused Drill Cutter Fastener Removal:

Conventional removal of the fastener was performed IAW best standard practices established for this operation. The test technician shall locate a pilot hole at the center of the fastener and step-drill that hole to the correct diameter for removal. A 500 RPM drill motor shall be used to perform the work and drill cutters shall be lubricated frequently and reused throughout the experiment. Cutters for each step size were selected from the batch of cutters used in test 7. Each reused cutter was then utilized for the remainder of this test.

Test method

a. Locate thermal imaging device in correct orientation to the area of interest
b. Install fastener
c. Center-punch fastener
d. Begin recording of thermal imaging device
e. Pilot drill fastener with 0.125” cobalt drill bit
f. Step drill fastener with 0.187” cobalt drill bit
g. Final drill fastener with 0.238” cobalt drill bit
h. Separate fastener via hand-punching
i. Stop recording on thermal imaging
j. Download image files
k. Record conditions
l. Repeat per Table 10

Coupon Processing Details:

Coupons were processed on 8/13/2020 and 8/18/2020 at Perfect Point’s facility. Test operation(s) were performed by Perfect Point EDM employee’s Bill Palleva and Jim Becker. All data recording and collection was performed by Joel Wells, an employee of FLIR Systems. Contact Perfect Point Engineering for his complete lab report.

The majority of this testing was witnessed by Kayna Trujillo, a Materials engineer for NAVAIR based at the US Navy repair depot North Island. Mrs. Trujillo directly witnessed test conditions 1-7 performed on 8/13/2020 but was not in attendance for the final processing of conditions 8-10 which were re-performed on 8/18/2020 due to a recording error on the thermal camera.

Test Results:

All test results are recorded in absolute Fahrenheit degrees. The average ambient temperature during testing was between 78-85°F. throughout this experiment. Positioning of the thermal camera remained constant throughout all test conditions and was 6.5” from the area of interest. Reported test temperatures and times were collected through logs created by the FLIR Research IR™ software and exported into a MS Excel™ .csv files for analysis. Duration of peak temperatures were identified as continuous time spent at the highest recorded temperature during each test.

Test Condition 01 (0.000" On-Center E-Drill Fastener Removal)

Test Condition 01 took direct thermal readings of the subject fastener and surrounding structure, while the coupon was oriented directly centered on the fastener head and stem.

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)	LH Structure Temp Peak [F]	RH Structure Temp Peak [F]
001-001	E-Drill	HL13V8	0.000	221.0	0.072	104.0	94.5
001-002	E-Drill	HL13V8	0.000	229.1	0.027	119.2	123.4
001-003	E-Drill	HL13V8	0.000	239.0	0.023	115.1	103.9
001-004	E-Drill	HL13V8	0.000	255.2	0.009	103.2	98.9
001-005-Steel	E-Drill	HL21PB8	0.000	239.0	0.018	110.9	97.6

[TABLE 2- TEST CONDITION 01]

Test Condition 02 (0.014" Offset E-Drill Fastener Removal)

Test Condition 02 took direct thermal reading of the subject fastener and surrounding structure, while the coupon was oriented 0.014" off-center of the fastener head and stem. This condition caused a material breach in the fastener which ejected a mixture of coolant water and metallic debris into the camera's field of view, preventing accurate recording after the loss of integrity.

A total offset of 0.014" was defined as the maximum offset limit for these specific fasteners and became the benchmark limit for breakout.

Test Condition 03 (0.013" Offset E-Drill Fastener Removal)

Test Condition 03 took direct thermal reading of the subject fastener and surrounding structure, while the coupon was oriented 0.013" off-center of the fastener head and stem. In this condition the fastener was oriented 0.001" from the breakout point and remained intact throughout the EDM process. The maximum temperature observed on the fastener was 711.2°F. with a total duration of 0.009 seconds and propagating on a small portion of the fastener (Figure 8). The maximum temperature observed in the surrounding structure was 174.3°F with a total duration of 0.036 seconds.

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)	LH Structure Temp Peak [F]	RH Structure Temp Peak [F]
003-001	E-Drill	HL13V8	0.013	663.8	0.005	143.3	143.3
003-002	E-Drill	HL13V8	0.013	622.1	0.009	143.6	101.1
003-003	E-Drill	HL13V8	0.013	711.2	0.009	162.6	174.5
003-004	E-Drill	HL13V8	0.013	600.1	0.005	130.3	103.6
003-005-Steel	E-Drill	HL21PB8	0.013	595.1	0.005	129.6	139.0

[TABLE 4- TEST CONDITION 3]

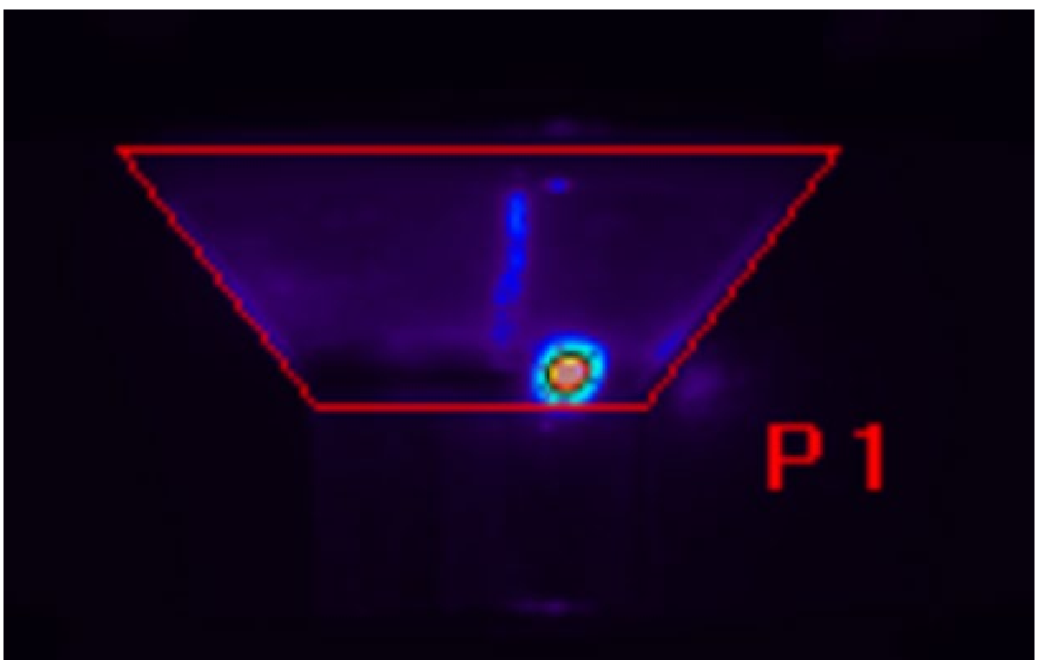


FIGURE 8: T/C 03-003- Peak Temp Visualization

Test Condition 04 (0.012" Offset E-Drill Fastener Removal)

Test Condition 04 took direct thermal reading of the subject fastener and surrounding structure, while the coupon was oriented 0.012" off-center of the fastener head and stem. In this condition the fastener was oriented 0.002" from the breakout point and remained intact throughout the EDM process. The maximum temperature observed on the fastener was 711.2°F. with a total duration of 0.005 seconds and propagating on a small portion of the fastener (Figure 9). The maximum temperature observed in the surrounding structure was 188.0°F with a total duration of 0.040 seconds.

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)	LH Structure Temp Peak [F]	RH Structure Temp Peak [F]
004-001	E-Drill	HL13V8	0.012	711.2	0.005	160.7	137.4
004-002	E-Drill	HL13V8	0.012	671.4	0.005	120.0	125.5
004-003	E-Drill	HL13V8	0.012	592.3	0.005	188.0	161.9
004-004	E-Drill	HL13V8	0.012	641.1	0.005	147.4	114.6
004-005-Steel	E-Drill	HL21PB8	0.012	575.5	0.005	164.2	171.7

[TABLE 5- TEST CONDITION 4]

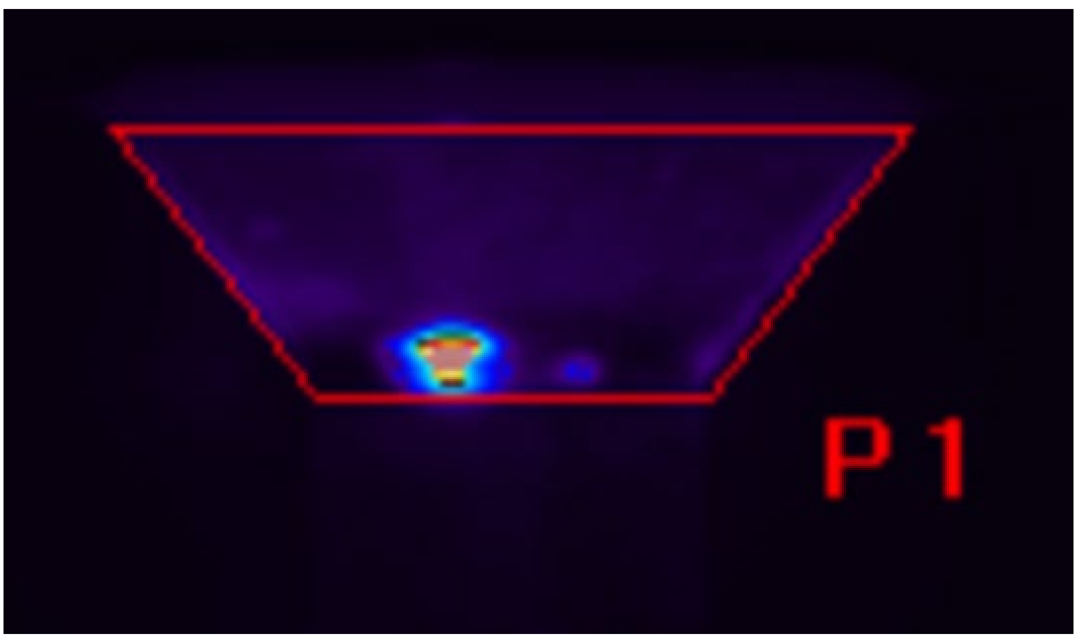


FIGURE 9: T/C 04-001- Peak Temp Visualization

Test Condition 05 (0.011” Offset E-Drill Fastener Removal)

Test Condition 05 took direct thermal reading of the subject fastener and surrounding structure, while the coupon was oriented 0.011” off-center of the fastener head and stem. In this condition the fastener was oriented 0.003” from the breakout point and remained intact throughout the EDM process. The maximum temperature observed on the fastener was 685.1°F. with a total duration of 0.014 seconds and propagating on a small portion of the fastener (Figure 10). The maximum temperature observed in the surrounding structure was 166.5°F with a total duration of 0.045 seconds.

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)	LH Structure Temp Peak [F]	RH Structure Temp Peak [F]
005-001	E-Drill	HL13V8	0.011	441.0	0.005	155.7	141.3
005-002	E-Drill	HL13V8	0.011	665.5	0.009	157.3	102.1
005-003	E-Drill	HL13V8	0.011	505.4	0.005	149.1	139.8
005-004	E-Drill	HL13V8	0.011	685.1	0.014	166.5	102.2
005-005- Steel	E-Drill	HL21PB8	0.011	400.0	0.009	115.1	123.4

[TABLE 6- TEST CONDITION 5]

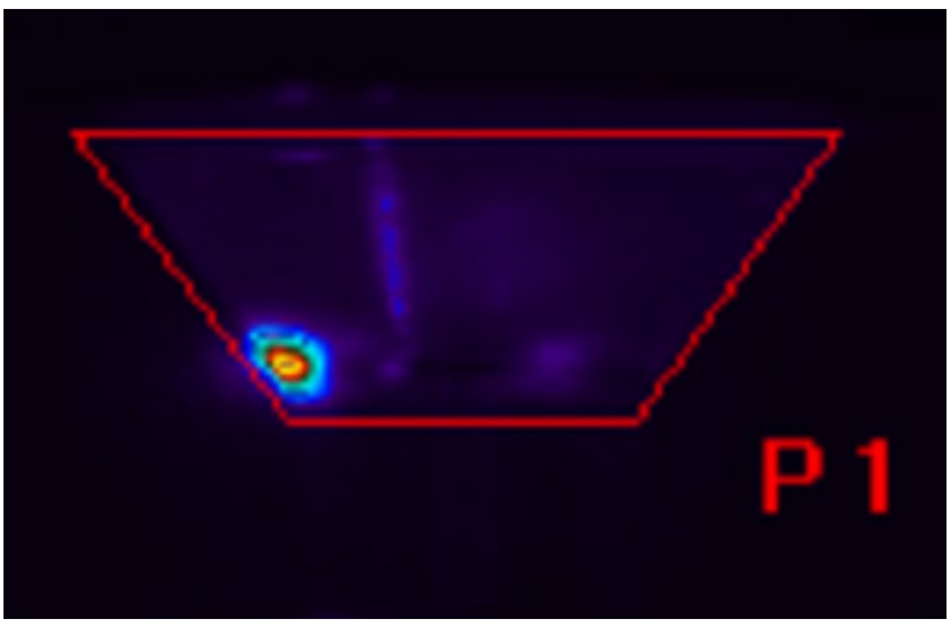


FIGURE 10: T/C 05-002- Peak Temp Visualization

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Test Condition 06 (0.010" Offset E-Drill Fastener Removal)

Test Condition 06 took direct thermal reading of the subject fastener and surrounding structure, while the coupon was oriented 0.010" off-center of the fastener head and stem. In this condition the fastener was oriented 0.004" from the breakout point and remained intact throughout the EDM process. The maximum temperature observed on the fastener was 516.0 °F. with a total duration of 0.014 seconds and propagating on a small portion of the fastener (Figure 11). The maximum temperature observed in the surrounding structure was 159.1 °F with a total duration of 0.059 seconds.

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)	LH Structure Temp Peak [F]	RH Structure Temp Peak [F]
006-001	E-Drill	HL13V8	0.010	447.8	0.005	110.4	114.8
006-002	E-Drill	HL13V8	0.010	231.0	0.027	110.0	107.4
006-003	E-Drill	HL13V8	0.010	516.0	0.014	106.0	99.6
006-004	E-Drill	HL13V8	0.010	282.0	0.009	116.2	113.8
006-005-Steel	E-Drill	HL21PB8	0.010	456.7	0.005	159.1	125.0

[TABLE 7- TEST CONDITION 6]

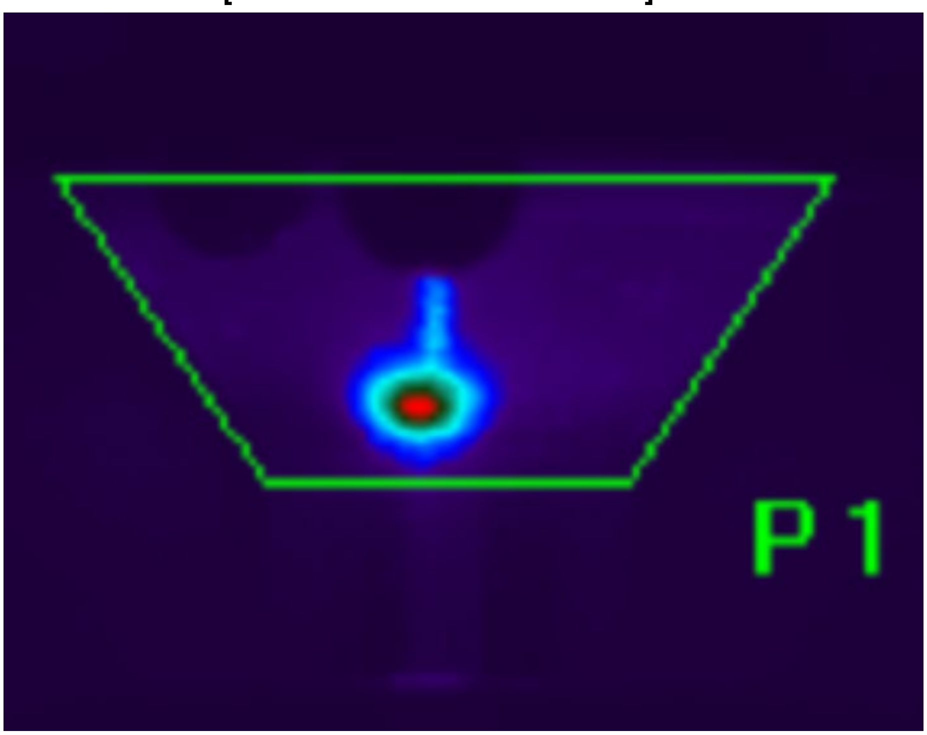


FIGURE 11: T/C 06-003- Max Temp Visualization

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Test Condition 07 (On-Centered Hand-Drill Fastener Removal- New Cutters)

Test Condition 07 took direct thermal reading of the subject fastener, while the coupon was bench-mounted in a rigid position. Due to test article movement and falling hot debris entering the camera's field of view, a continuous recording of the surrounding structure proved difficult to perform. Random sampling of the surrounding structure indicated an average temperature of 120-180°F. As that was nearly identical to the temperatures recorded by the E-Drill process it was decided to not perform continuous monitoring of the coupon structural temperature. Thermographic recording of the fastener during the hand-drilling process was possible but was not as accurate as that of the E-Drill. A 30Hz recording cycle was performed on this series due to the technical challenges described above and due to the process' duration.

In this condition the fastener was hand-drilled out on-center. The maximum temperature recorded was 687.9°F had a total duration of 0.400 seconds and propagated on a large area of the fastener (Figure 12).

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)
007-001	Hand Drill	HL13V8	~0.000	473.9	0.231
007-002	Hand Drill	HL13V8	~0.000	485.4	0.133
007-003	Hand Drill	HL13V8	~0.000	608.9	0.363
007-004	Hand Drill	HL13V8	~0.000	687.9	0.400
007-005-Steel	Hand Drill	HL21PB8	~0.000	482.2	0.792

[TABLE 8- TEST CONDITION 7]

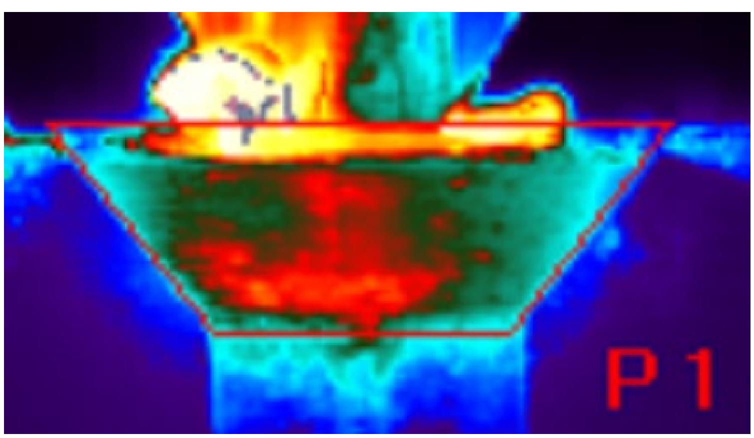


FIGURE 12: T/C 07-004- Max Temp Visualization

Test Condition 08 (Direct EDM Cutting- Aluminum Sheet)

Test Condition 08 took direct thermal reading of an EDM cut into a 0.125" thick aluminum coupon sheet, as viewed from the exit side of the cut location. The E-Drill was configured to a depth of cut of 0.120" thereby leaving a 0.005 web between the thermal camera and the cutting electrode. The maximum temperature observed was 250.7°F. with a total plot of the heat ramping showed an average duration of 1-2 seconds and an immediate quenching upon completion of the cut. (Figure 13-14).

Test Condition	Peak Temp [F]
008-001	250.7
008-002	216.9
008-003	229.5
008-004	232.9
008-005	234.0

[TABLE 9- TEST CONDITION 8]

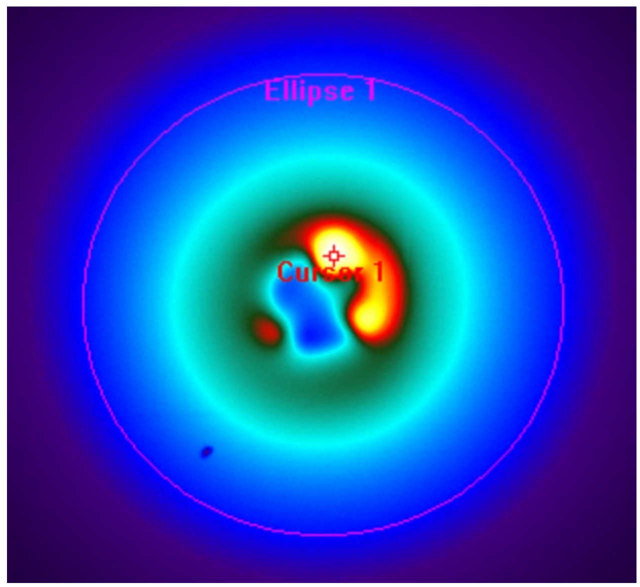


FIGURE 13: T/C 08-001- Max Temp Visualization

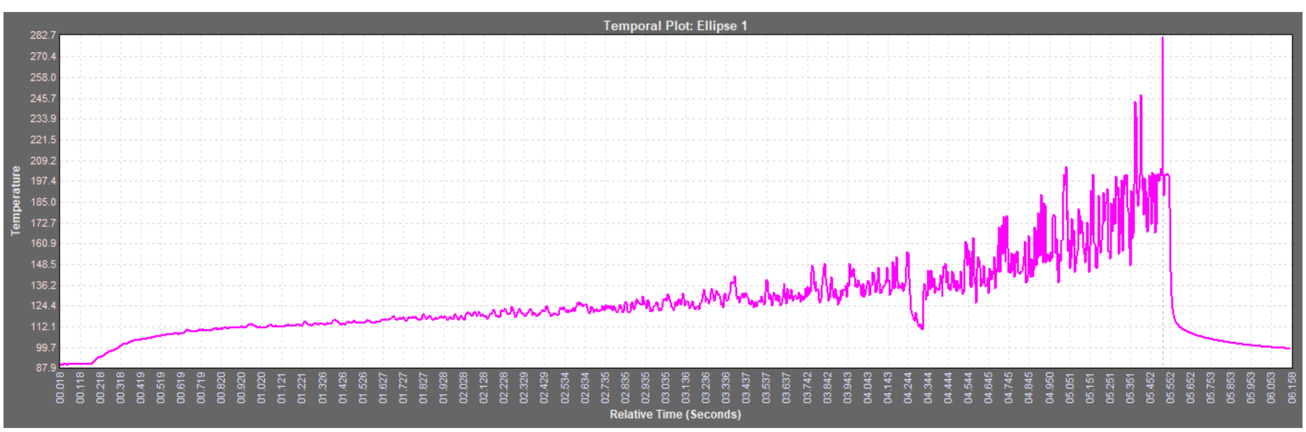


FIGURE 14: T/C 08-001- Cut Cycle Thermal Profile

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Test Condition 09 (Direct EDM Cutting- Titanium Sheet)

Test Condition 09 took direct thermal reading of an EDM cut to a 0.125" thick Titanium coupon sheet, as viewed from the exit side of the cut location. The E-Drill was configured to a depth of cut of 0.120" thereby leaving a 0.005 web between the thermal camera and the cutting electrode. The maximum temperature observed was 413.1°F. with a total plot of the heat ramping showed an average duration of 1-2 seconds and an immediate quenching upon completion of the cut. (Figure 15-16).

Test Condition	Peak Temp [F]
009-001	305.2
009-002	385.0
009-003	390.9
009-004	413.1
009-005	404.8

[TABLE 10- TEST CONDITION 9]

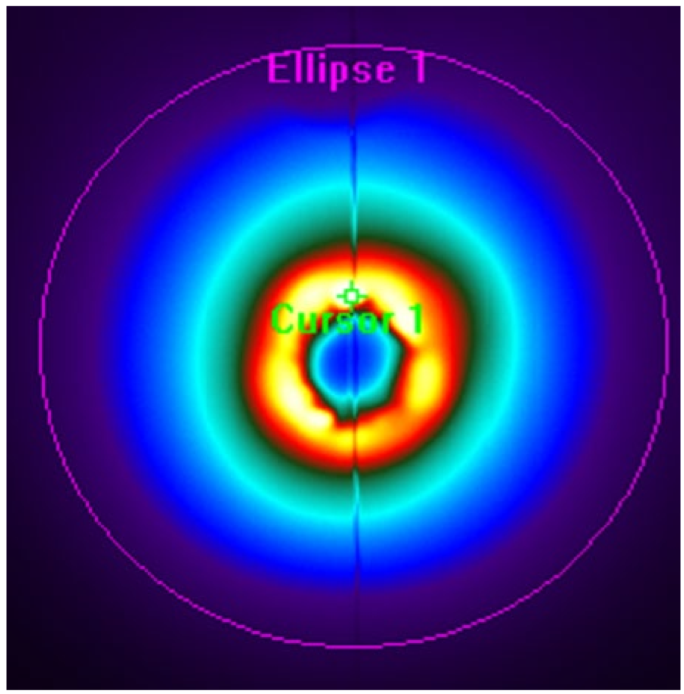


FIGURE 15: T/C 09-004- Max Temp Visualization

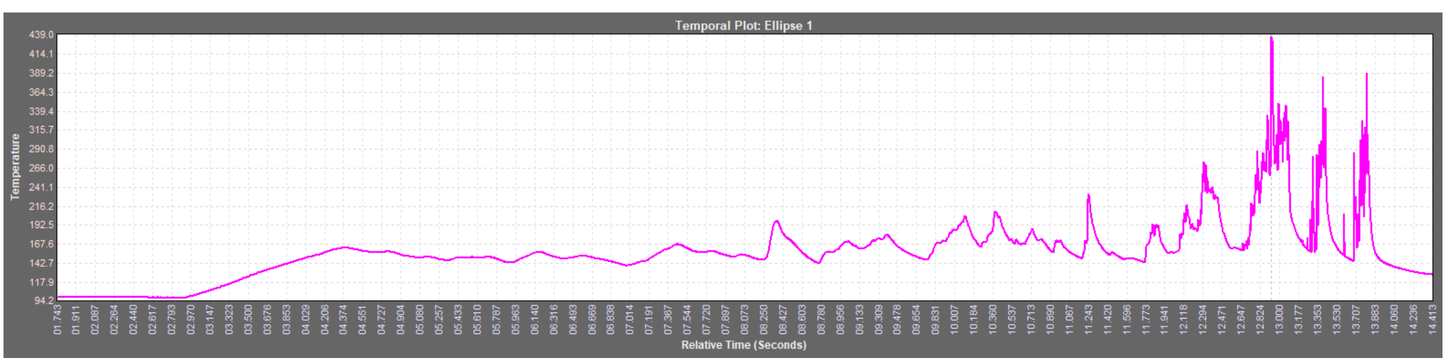


FIGURE 16: T/C 09-004- Cut Cycle Thermal Profile

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Test Condition 10 (On-Centered Hand-Drill Fastener Removal- Reused Cutter)

Test Condition 10 took direct thermal reading of the subject fastener while the coupon was bench-mounted in a rigid position, and the recording process was duplicated from Test Condition 007.

In this condition the fastener was hand-drilled out on-center (visually unaided). The maximum temperature 700.1°F and had a total duration of 0.198 seconds and propagated on a large area of the fastener (Figure 17).

Test Condition	Process	Fastener	Offset From Center	Fastener Peak Temp [F]	Duration of Peak Temp. (seconds)
010-001	Hand Drill	HL13V8	~0.000	525.9	0.363
010-002	Hand Drill	HL13V8	~0.000	700.1	0.198
010-003	Hand Drill	HL13V8	~0.000	571.6	0.198

[TABLE 11- TEST CONDITION 10]

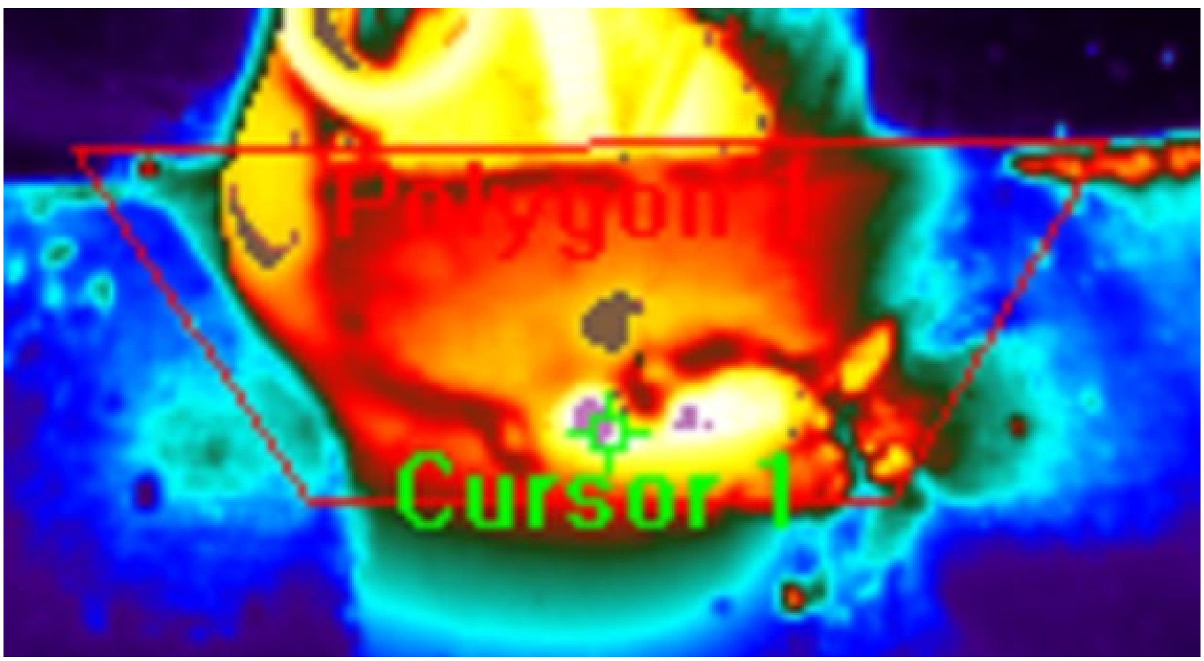


FIGURE 17: T/C 10-002- Max Temp Visualization

Perfect Point™
15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Data Analysis:

Individual Test Point Results

The primary objective of the testing was to determine peak temperatures for the surrounding structures and fastener in each test case. Throughout the experiments the thermal camera logged time and temperature for the entire field of view, with the key focus areas being the fastener and the structure directly adjacent [Figure 19]. E-Drill and Hand-Drill base line conditions (Tests 1-7) were used as a direct comparison between the two processes. Test 10 was intended to be replicated five times but following the completion of the third iteration the drill cutters used for the experiment were deemed no longer serviceable and the test was terminated prematurely.

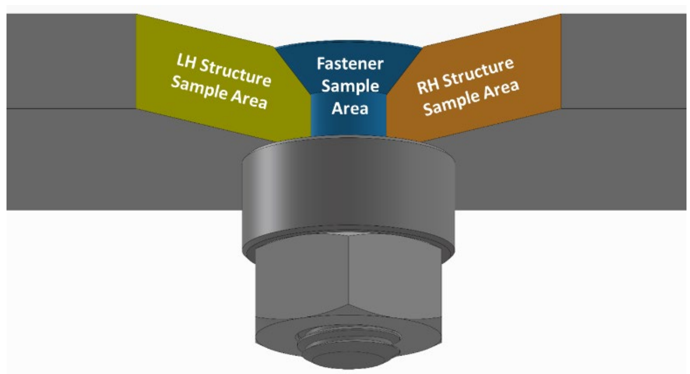


FIGURE 18: Temperature Sampling Locations

Test Condition	Offset From Center	E-Drill Cut Time (seconds)	Peak Fastener Temp [F]	Duration of Peak Temp. (seconds)	Structure Temp Peak LH [F]	Structure Temp Peak RH [F]
001-001	0.000	13.2	221.0	0.5085	104.0	94.5
001-002	0.000	13.8	229.1	0.0945	119.2	123.4
001-003	0.000	14.1	239.0	0.1845	115.1	103.9
001-004	0.000	14.0	255.2	0.0855	103.2	98.9
001-005-Steel	0.000	15.0	239.0	0.1440	110.9	97.6
002-001	Fastener Breakout Boundry Discovered at 0.014" Offset From Center (Test Baseline)					
003-001	0.013	13.0	663.8	0.0495	143.3	143.3
003-002	0.013	14.0	622.1	0.0900	143.6	162.6
003-003	0.013	11.9	711.2	0.0765	115.1	174.5
003-004	0.013	12.8	600.1	0.0360	130.3	103.6
003-005-Steel	0.013	14.3	595.1	0.0270	129.6	139.0
004-001	0.012	14.7	711.2	0.0405	160.7	137.4
004-002	0.012	13.8	671.4	0.0225	120.0	125.5
004-003	0.012	12.2	592.3	0.0225	188.0	161.9
004-004	0.012	13.9	685.1	0.0450	147.4	114.6
004-005-Steel	0.012	14.2	575.5	0.0675	164.2	171.7
005-001	0.011	14.4	441.0	0.0810	155.7	141.3
005-002	0.011	15.2	665.5	0.0765	157.3	102.1
005-003	0.011	12.3	505.4	0.0540	149.1	139.8
005-004	0.011	13.4	685.1	0.0900	166.5	102.2
005-005-Steel	0.011	12.9	400.0	0.0855	115.1	123.4
006-001	0.010	15.4	447.8	0.1080	110.4	114.8
006-002	0.010	14.8	231.0	0.2970	110.0	107.4
006-003	0.010	13.0	516.0	0.2655	106.0	99.6
006-004	0.010	14.1	282.0	0.1215	116.2	113.8
006-005-Steel	0.010	13.5	456.7	0.0495	159.1	125.0

Table 12: Individual E-Drill Test Results

Test Condition	Offset From Center	Hand-Drill Cut Time (seconds)	Peak Fastener Temp [F]	Duration of Peak Temp. (seconds)
007-001	~ 0.000	108.4	473.9	0.231
007-002	~ 0.000	174.9	485.4	0.133
007-003	~ 0.000	176.5	608.9	0.363
007-004	~ 0.000	137.5	687.9	0.400
007-005-Steel	~ 0.000	111.5	482.2	0.792
010-001	~0.000	111.1	525.9	0.363
010-002	~0.000	124.1	700.1	0.198
010-003	~0.000	131.7	572.2	0.198

Table 13: Individual Hand-Drill Test Results

Baseline interrogation of the fastener identified the breakout boundary zone at 0.014” offset from center. Breakout is defined as the condition in which the E-Drill cutting electrode escapes the fastener body. Offset test configurations were then defined as 0.000” and 0.010-0.013”.

Throughout all E-Drill tests the highest recorded temperature in the surrounding coupon structure was 188°F (absolute) with a total duration of 0.045 seconds. Heated debris falling into the camera’s field of view prevented continuous monitoring of the coupon structure throughout the Hand-Drilling process, however, individual sampling performed throughout the test indicated maximum temperatures in the 150-180°F range. As neither of these temperatures were sufficient for any practical concern, no further analysis was performed on the coupon structure.

Fastener temperature varied throughout testing but remained consistent throughout each tested condition and there was no significant difference between Titanium and Alloy-Steel fasteners noted throughout any test condition.

Fasteners processed by E-Drill displayed higher peak temperatures as the E-Drill was offset towards the breakout location, with 711.2°F for 0.009 seconds being recorded as the highest individual absolute temperature and duration when the coupon was located 0.001" from the breakout boundary. As the offset was reduced, so did the corresponding temperatures and durations. On-centered E-Drill processing resulted in a maximum temperature of 255.2°F for a total duration of 0.01 seconds.

Fasteners processed by hand-drilling displayed similar peak temperatures to those of offset E-Drill processing, with 687.9°F for a duration of 0.400 seconds being recorded as the maximum recorded temperature and duration. Temperature peaks greater than 450°F were observed in every instance of controlled hand drilling.

Test Averages

All testing for E-Drill and Hand Drill conditions (Tests 1-7) were repeated five times to establish an average baseline. The individual values for each experiment were recorded and then averaged to produce a more statistically relevant dataset for review. In all cases, the coupon structure did not record temperatures of any significance and the fastener was the most radiant object in the recording.

Test Condition Averages	Process	Offset From Center	Peak Temp (Fastener) [F]	Duration of Peak Temp. (seconds)
TC-001	E-Drill	0.000	236.7	0.030
TC-003	E-Drill	0.013	638.5	0.006
TC-004	E-Drill	0.012	638.3	0.005
TC-005	E-Drill	0.011	539.4	0.008
TC-006	E-Drill	0.010	386.7	0.012
TC-007	Hand Drill	~0.000	547.7	0.384
TC-010	Hand Drill	~0.000	599.2	0.253

Table 14: Averaged Test Results

Test 10 was intended to be replicated five times but following the completion of the third iteration the drill cutters used for the experiment were deemed no longer serviceable and the test was terminated prematurely after only three complete cycles.

Test cases of on-center E-Drill processing against on-center hand-drill processing revealed E-Drill produced peak average temperatures ~300°F less than the hand-drill process.

Test cases of off-centered E-Drill processing (0.010 off-center) revealed average peak temperatures for E-Drill were ~150°F lower than those of on-centered hand-drilling using industry best practices. Test cases of off-centered E-Drill processing (0.011- 0.013 off-center) revealed average peak temperatures for E-Drill were ~90°F higher than those of on-centered hand-drilling using industry accepted best practices.

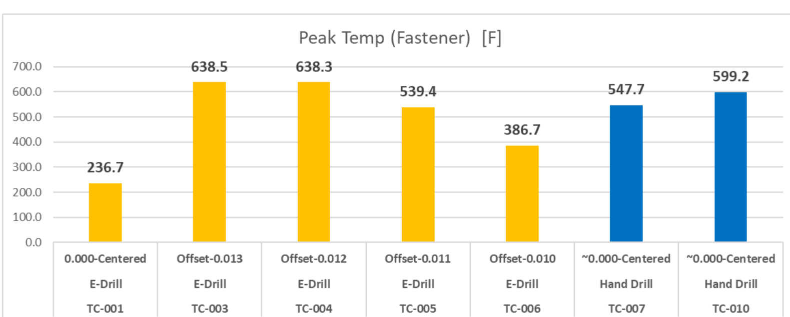


FIGURE 19: Averaged Peak Temperatures

Throughout the tests average E-Drill peak durations were between 0.005-0.030 seconds, compared to an average duration of 0.384 seconds of hand-drilling.

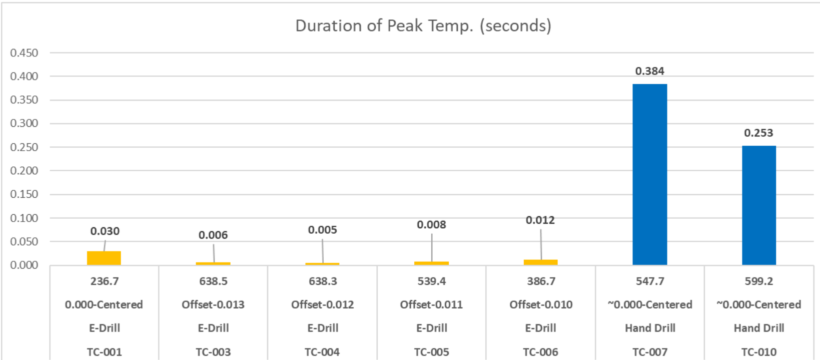


FIGURE 20: Averaged Peak Durations

Time Spent at Significant Temperatures

To complete the analysis, Perfect Point collaborated with several aerospace engineering organizations to determine what temperatures were of significance to the technical community. 250, 350 and 500°F were identified as temperature ranges that were of significance and were also documented in this investigation. These target temperatures were then used to filter the data logs recorded by each test condition to determine how long, if at all, the subject fastener's outer layer reached these targets. [Table 15]

Test Condition Averages	Process	Offset From Center	Peak Temp (Fastener) [F]	Duration of Peak Temp. (seconds)	Duration of +500 °F. (seconds)	Duration of +350 °F. (seconds)	Duration of +250 °F. (seconds)
TC-001	E-Drill	0.000	236.7	0.030	0.000	0.000	0.002
TC-003	E-Drill	0.013	638.5	0.006	0.010	0.023	0.104
TC-004	E-Drill	0.012	638.3	0.005	0.007	0.026	0.128
TC-005	E-Drill	0.011	539.4	0.008	0.008	0.017	0.063
TC-006	E-Drill	0.010	386.7	0.012	0.004	0.015	0.059
TC-007	Hand Drill	~0.000	547.7	0.384	1.359	6.300	33.672
TC-010	Hand Drill	~0.000	599.2	0.253	1.399	10.090	40.737

[Table 15- Averaged Time Spent at Significant Temperatures]

Each test result was exported into an MS Excel™ spreadsheet and filtered by the "count-if" function, that identified individual frames with temperatures greater than the target. The sum of the frames was then assigned the appropriate time duration (E-Drill Frame= 0.0045 seconds and Hand-Drill Frame = 0.0333 seconds).

The data shows a record for each test condition and iteration but is not to be interpreted as continuous time spent above that target temperature. Hand-drilling cases displayed numerous excursions beyond the +350-500°F target limit, whereas E-Drill typically had only 3-4 events near that range which peaked and diffused quickly.

Significant differences between the two processes were identified. In every test case E-Drill did not see any significant heating (+250°F) until the last 1-2 seconds of its process and had typical dwell averages in the 100-165°F range [Figure 25] for most of the process.

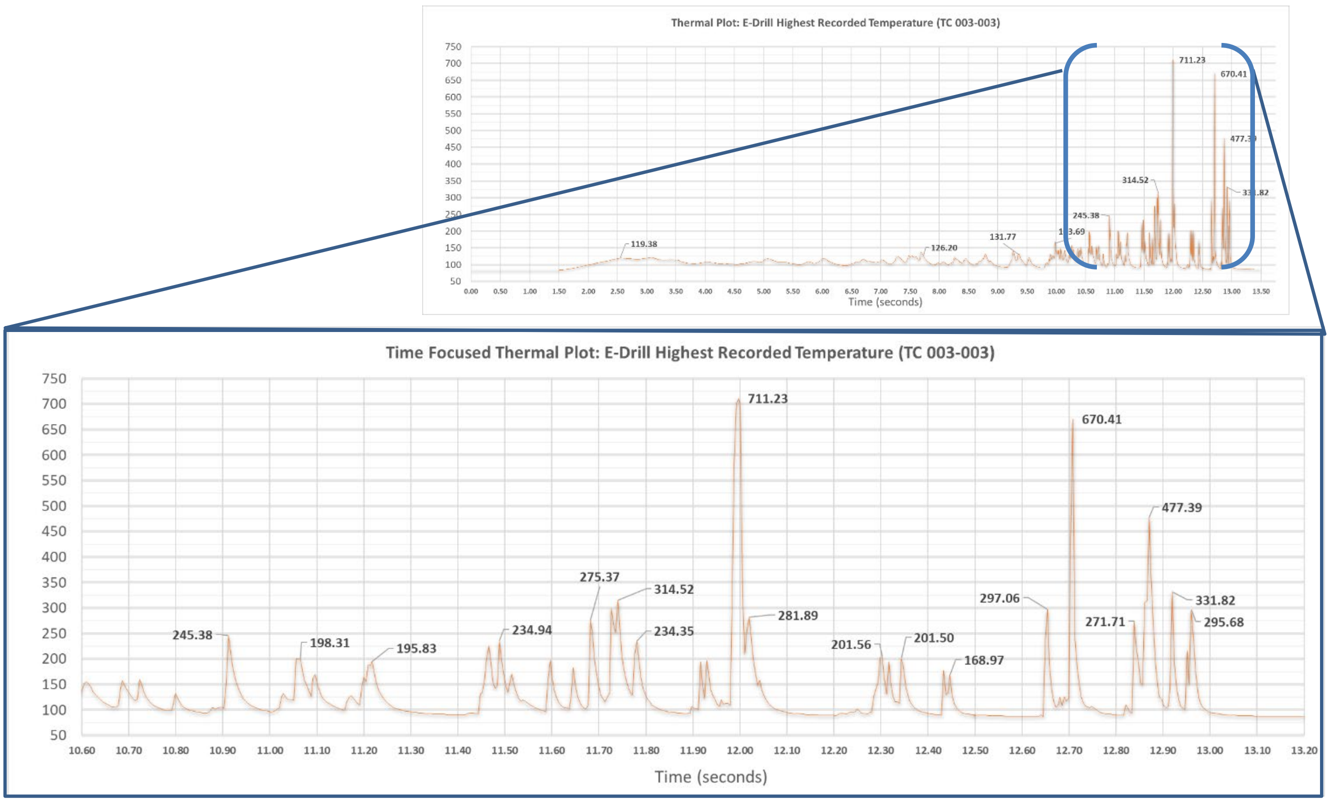


FIGURE 21: E-Drill Peak Intensity (Focused View)

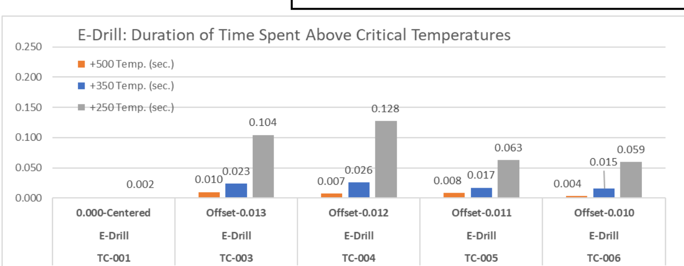


FIGURE 22: Averaged E-Drill Durations Above Critical Temperatures

Throughout all tests E-Drill performance remained constant and showed a functional relationship between the amount of offsetting and temperature intensity. On-centered E-Drill processing yielded the lowest temperatures and durations, whereas offsets 0.001-0.003” from the breakout zone yielded the highest. At 0.004” from breakout there was a significant drop in temperature and duration as compared to performance recorded at 0.001-0.003” from the breakout zone.

In every test case Hand-Drill processing yielded immediate spiking into temperatures of interest.

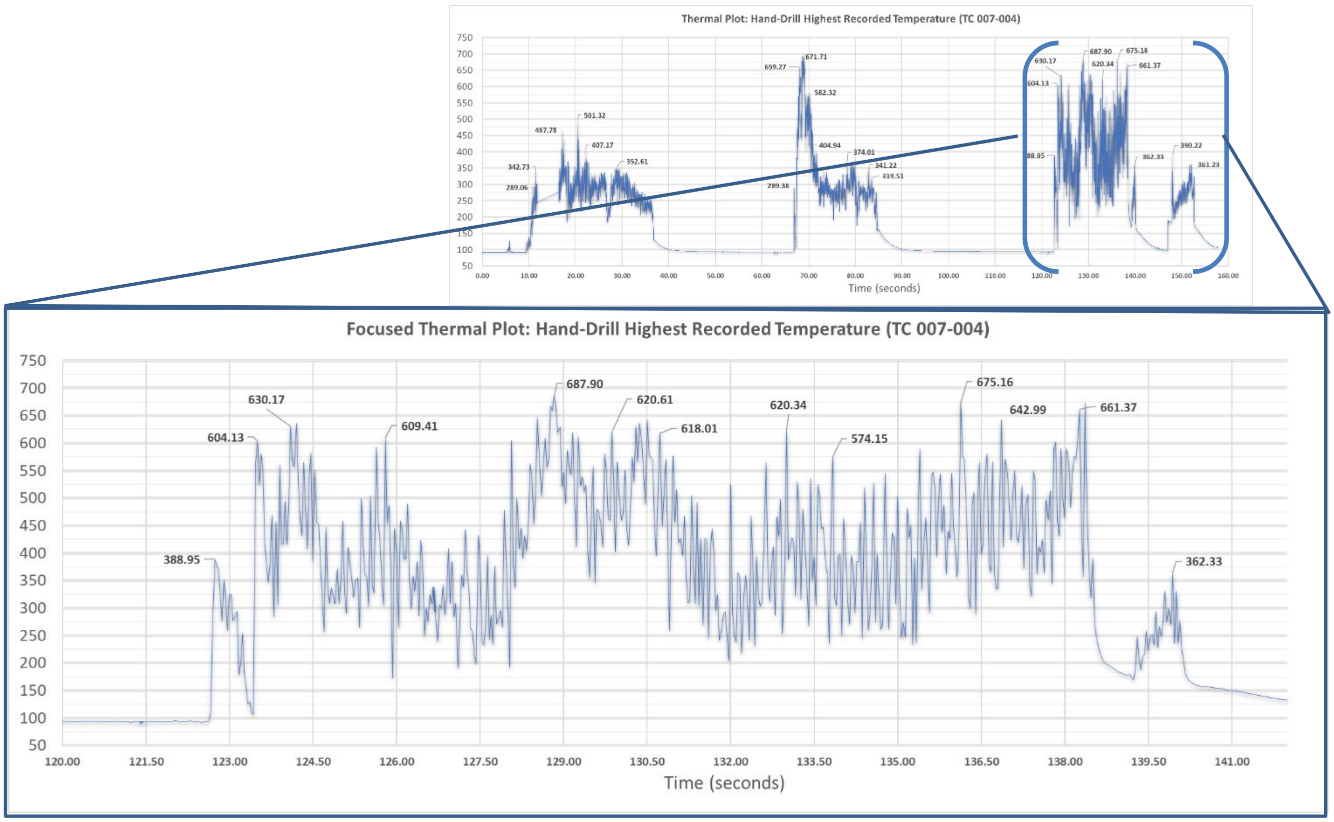


FIGURE 23: Hand-Drill Peak Intensity (Focused

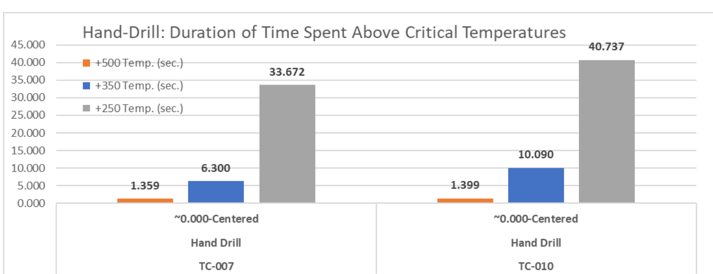


FIGURE 24: Averaged Hand-Drill Durations Above Critical Temperatures

Throughout all tests Hand-Drill performance showed a functional relationship to the downward force applied to the cut area and the diameter of the cutting bit. Cutting with a 0.125" drill yielded peak temperatures averaging in the 250-450°F range, whereas step-drilling and final size drilling (0.187" and 0.238") peaked in the 500-650°F range. Typically, the spikes to peak temperature in each step occurred immediately after the drill process began and fluctuated through the step in-relation to the operator's downward force applied to the cut location. Of note during testing when a reused drill cutter was used, temperature durations were significantly higher.

15192 Triton Lane
Huntington Beach, CA 92649
Office Tel: 714-892-3400
Hotline Tel: 714-891-6533
www.ppedm.com

Conclusions:

During the course of this experiment, there were no significant transfers of thermal energy from either E-Drilling or Hand-Drilling transmitted to the surrounding structure, in which a fastener was installed.

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 exists 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 heating, E-Drill temperature values exist for significantly less time than currently accepted Hand-Drilling values.

The typical process time for the E-Drill cutting cycle was between 12-13 seconds consistently throughout the testing. Typical Hand-Drilling process time was between 100-175 seconds throughout the testing. E-Drill coupon processing was a short, controlled, and secure method producing no movement or debris in the testing, whereas Hand-Drilling was a longer disruptive method producing significant amounts of debris and movement.

While this testing does not encompass every scenario a E-Drill might be used upon, it can be stated that the correct use of E-Drill is no more disruptive than currently acceptable Hand-Drill methods, when removing solid Titanium and Steel-Alloy fasteners. In every case tested, E-Drill produced significantly shorter processing times, lower durations of significant heat, and produced no drilling shards or swarf.