Microstructure Effects of the Electrical Discharge Machining Drill on Aerospace Super Alloys

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This paper presents an analysis of the parent material damage and electrode wear of a handheld electrical discharge machining (EDM) drill. The motivation of this study is to investigate the material effects of EDM drilling on aerospace alloys at a microstructure level. The specific effects that are being investigated are heat affected zones (HAZ), grain structure changes, material composition changes, and fracturing. A secondary goal of this study is to determine if there is potential for electrode wear prediction models for supply chain management. The study consisted of making cuts into both Inconel and titanium test specimens while varying cut depths and electrode diameters. The results of the study found that the electrode wear while cutting Inconel showed some amount of predictable behavior. On the contrary, the titanium specimens did not indicate a predictable behavior and did not appear to follow an intuitive trend. Interestingly, when drilling into titanium, the active electrode increased in length, indicating that the titanium is being deposited onto the electrode. The EDM drill caused notable damage to the parent material, including a substantial recast layer of up to approximately 150 μm in thickness, incorporation of electrode material into the parent material through the recast layer, and formation of microcracks that can cross the recast layer/parent material interface. These noted characteristics can have an impact on material performance and longevity due to the nonuniform nature of the damage and the introduction of microcracks crossing from the recast layer into the parent material.

1. Introduction

Conventional fastener removal methods require fasteners to be drilled out through the main body then removing any keys keeping the fastener in place. These methods typically involve elevated noise levels, high drill speeds, and large normal force requirements. In addition, in-process misalignment and significant environmental, health, and safety concerns are often an issue with conventional removal. There is a demand in the aerospace maintenance, repair, and overhaul (MRO) industry to develop tools and practices to avoid these drawbacks. EDM drilling is a well-established method and has emerged as a fast, portable means for fastener removal with minimal debris, noise, misalignment, and normal force. Use of EDM hand drills has been shown to reduce fastener removal times from over 5 minutes to under 10 seconds. Furthermore, it prevents debris, hole burrs, and hole drift that are common with mechanical drilling and cutting. EDM hand drills use a consumable electrode as the cutting tool. As with any repair process, there is always a risk of damage to the parent material. Quantifiable damage analysis of the EDM drill process is valuable to the operators and the repair development team in order to properly assess repair methods for field application. The purpose of this study is to analyze parent material damage and electrode wear of a handheld EDM drill (Perfect Point™ Edrill™). This study can be applied to all MRO operations as well as aircraft turbine engine sustainment procedures. Typically, titanium and Inconel alloys are difficult to machine due to their high strength qualities, which necessitates the need for EDM when machining. Similar studies have been conducted to investigate the relationship of EDM current and voltage parameters to recast layer and HAZ [1–3]. In scenarios that involve a high volume of aerospace fastener removal, large
amounts of electrodes may be consumed; therefore, an electrode supply chain may be difficult to predict and could lead to shortages or, in the alternative, a large electrode surplus. The electrode wear study serves to be an indicator test for future analysis and development of a predictive electrode supply chain model. Micro EDM hole drilling is a similar process; however, small holes (diameter less than 1 mm) are cut instead of large. Aligiri et al. have documented an investigation on Micro EDM tool wear in order to develop an accurate mathematical wear model [4]. Yilmaz et al. have a well-documented experiment with deep hole Micro EDM with hole depths up to 20 mm, following similar EDM parameters such as material removal rate, electrode wear rate, and relative wear [5].

2. Background

Though first discovered in 1770, the common application of EDM for material removal began in the 1940s and has evolved into three major variations: Die Sinker “Ram” EDM, Wire EDM, and Hole Drilling EDM [6–8]. The unifying principle behind the three types is relatively simple; an electrical current passes between an electrode and a metal workpiece which are separated by a dielectric liquid. The fluid serves as an electrical insulator until sufficient voltage is applied to achieve its ionization point. The fluid then behaves as an electrical conductor, such that a resultant spark discharge erodes or vaporizes some of the workpiece. The dielectric fluid also serves to flush tiny bits of the eroded material away from the workpiece and electrode. The process is sustained by maintaining a consistent gap between the electrode and the work piece. Ram EDM involves plunging a custom electrode to effectively stamp a shape into the workpiece. Wire EDM (WEDM) uses a thin wire for an electrode, moving and cutting a path through the workpiece [9–11]. Figure 1 shows a simple schematic to illustrate a typical hole drilling EDM process, in which a rotating, cylindrical electrode tube plunges into the workpiece to form a hole. A guide ensures the desired hole path is maintained. This process has been used with aircraft gas turbines to drill cooling holes into very hard metal alloy blades and vanes with highly curved shapes. Along with the aforementioned types of EDM, another worth mentioning is Powder Mixed EDM (PMEDM) and its effects on superalloys [12]. In this form of electron discharge machining, a material in powder form is mixed with the dielectric fluid of the EDM in order to improve some machining characteristics of EDM machining.

Recently, Perfect Point patented a hand-held EDM drill for fastener removal [13]. Operation involves the programming type, size, and fastener material into the tool to set cut parameters. The tool cuts to the bottom of the fastener head, short of penetrating through it, as shown in Figure 2. The cut diameter is within that of the fastener head and shaft so that the electrode does not come into contact with the skin, fastener hole, or substructure. A key step in the operation involves carefully placing the locator to center the tool on the fastener. After the cut is made, a punch tool taps out the fastener head to separate the head from the shank, and the head is then retrieved.

2.1. Micro EDM. Ay et al. [14] investigated how pulse duration and pulse current influence hole quality in Micro EDM hole drilling into Inconel 718. A Gray relational analysis was used to analyze the data gathered from a Sodick AP1L die-sinker EDM machine cut with a 500 mm diameter, copper-tungsten electrode. It was found that hole taper ratio, hole dilation, and electrode wear each increased almost linearly with an increase in pulse duration and current. The machined surfaces also had more damage and cracking with increased pulse duration and current.

Yilmaz & Okka [15] studied the electrode performance difference between 1 mm diameter single channel and multichannel electrodes made of brass and copper for EDM fast hole drilling into Inconel 718 and Ti–6Al–4V. Comparisons were made between the material removal rate, electrode wear, microhardness, and scanning electron microscope (SEM) images. The results indicated that the single channel electrode has superior electrode wear and material removal rates, and the brass electrodes obtained a higher material removal rate. However, the copper electrodes experience lower wear rates in both single and multichannel types. The multichannel electrodes produced finer surface finishes than the single channel. This is likely due to the better flushing ability of the multichannel electrode. Finally, the HAZ layer of the holes indicates a gradually decreasing hardness with increasing distance from the hole entrance.

Caydas and Hasicak [16] attempted to model EDM electrode wear and recast layer thickness through response surface methodology. The variables were pulse on time, pulse off time, and pulse current. Pulse current was found to be the most influential parameter in electrode wear and recast layer thickness, but pulse off time has no significant effect. Li et al. [17] studied the effects of different dielectric fluids on the recast layer. It was found that the recast layer thickness would increase as the dielectric fluid electrical conductivity increased, with kerosene producing the lowest thickness recast layer. The cooling ability of the dielectric fluid would affect the grain structure of the recast layer. Li et al. [18] looked at different wire EDM process modes to improve machined surface finish. The modes used were a rough cut mode and three trimming modes. The rough cut mode had the highest discharge energy, whereas the last trim
mode had the lowest discharge energy. With each reduction in discharge energy, the recast layer was reduced.

3. Materials and Methods

3.1. Electrode Wear Experiment Setup. An electrode study was accomplished to evaluate (1) cut process repeatability as a function of cut depth, electrode diameter, and material type, (2) parent material characterization after direct contact with electrode, and (3) to determine if there is potentially predictable electrode wear behavior. Tables 1 and 2 illustrate the chemical composition of titanium and Inconel work pieces, respectively. Grade 5 titanium was used in the experiment due to its common use in the aerospace industry and can be found in various turbine engine components. It has a great combination of strength and corrosion resistance. Inconel 718 has the same applications and material properties but with a greater heat resistance than that of Grade 5 titanium.

Table 3 shows the test matrix for the electrode study. The study was accomplished with the Perfect Point™ E-Drill™, cutting into the surface of the titanium and Inconel work piece specimens with a copper alloy electrode. Each task was performed 3 separate times as noted in the “Number of Cuts” column. These 3 cuts are used to calculate the mean shown in a later section. More cuts could have been done, but the cost of the Perfect Point™ electrodes restricted a higher number of cuts along with a lack of electrodes resulting in the inability to have varying electrode sizes for Inconel; however, there were enough varying electrode sizes for the titanium material. The experimental setup for this study consisting of the Perfect Point™ E-Drill™, a table vice, the electrode guide, and a 3D printed polylactic acid (PLA) jig. This special jig was designed to ensure consistent location of the cut over the hole. The jig and specimen were clamped in a table vice to further ensure consistency. When using the EDM, the user places the end of the EDM into the electrode guide and then holds down the button, while the electrode makes the cut. Little physical effort is needed for this process.

The process parameters of the E-Drill™ including peak current, voltage, pulse duration, pulse interval, and rotation of electrode are proprietary information of Perfect Point™ and are unavailable to be obtained; however, one process parameter that is public knowledge is that of the dielectric fluid. The dielectric fluid for the E-Drill™ is tap water.

Figure 3 shows the test arrangement and a photo of an example cut that reveals key features such as splatter and the heat affected zone. Specimens from this study were also evaluated for surface and subsurface material characterization to evaluate potential damage due to misaligned E-Drill™ cuts. These particular results will be in an upcoming section.

Figures of merit considered for the electrode study include Radial Electrode Wear (ε_r), as shown in equation (1), where ΔO and ΔI are the changes in the outer and inner
### Table 3: Electrode study test matrix.

| Task | Cut depth (mm) | Electrode diameter (mm) | Material     | Number of cuts |
|------|----------------|-------------------------|--------------|----------------|
| 1.1  | 1.27           | 8.382                   | Inconel 718  | 3              |
| 1.2  | 2.54           | 8.382                   | Inconel 718  | 3              |
| 1.3  | 3.81           | 8.382                   | Inconel 718  | 3              |
| 2.1  | 1.27           | 8.382                   | Ti-6A-4V     | 3              |
| 2.2  | 2.54           | 8.382                   | Ti-6A-4V     | 3              |
| 2.3  | 3.81           | 8.382                   | Ti-6A-4V     | 3              |
| 3    | 2.54           | 4.762                   | Ti-6A-4V     | 3              |
| 4    | 2.54           | 3.175                   | Ti-6A-4V     | 3              |

**Figure 3:** Testing arrangement (a) and cut made during electrode wear study (b).

**Figure 4:** SEM micrographs of electrode wear study for Inconel.
diameters of the electrode in mm, respectively, the Material Removal Rate ($\mu$), as shown in equation (2), where $A_c$ is the area of the cut in mm$^2$, $H$ is the depth of the cut in mm, and $T$ is the time of the cut in seconds; Electrode Wear Ratio ($\zeta$), as shown in equation (3), where $\Delta V_e$ is change in electrode volume in mm$^3$, and $\Delta V_{fm}$ is the change in workpiece volume in mm$^3$; and Axial Electrode Wear ($\epsilon_a$), as shown in equation (4), where $L_b$ is the axial length of the electrode before the cut in mm, and $L_a$ is the axial length of the electrode after the cut in mm.

$$\epsilon_r = \Delta O + \Delta I,$$  
(1)

$$\mu = \frac{A_c * H}{T},$$  
(2)

$$\zeta = \frac{\Delta V_e}{\Delta V_{fm}},$$  
(3)

$$\epsilon_a = L_b - L_a.$$  
(4)

The Radial Electrode Wear (RAW), Material Removal Rate (MRR), Electrode Wear Ratio (EWR), and Axial Electrode Wear (AEW) were chosen due to their significance in understanding the process that occurs during the EDM use. These figures of merit or parameters were evaluated using dial callipers in order to get the most accurate measurements before and after the experiments were completed. The RAW analyses the wear of the electrode radially by taking precise measurements of the inner and outer diameter of the electrode before and after the EDM process with the dial callipers. The MRR analyses the removal rate of the parent material by the electrode. The EWR is obtained by taking the area of the cut which can be found from the diameter of the electrode and multiplying the area by the height of the cut. The height of the cut is a value programmed into the E-Drill™ by the user when setting up the experiment. The volume of the cut is then divided by the time of the cut, and this is tracked by the E-Drill™ on the interface screen. The EWR analyses the volume of the electrode compared to the volume of the parent material to see if there are any material depositions by one on to the other. This is measured by comparing the volumes of the electrode and parent material before and after the experiment is completed. Finally, the AEW analyses the wear of the electrode axially to see if the electrode gains or loses length during the EDM process. The AEW is found by measuring the length of the electrode before and after the cut with the dial callipers.

4. Results and Discussion
4.1. Microstructure Results. Polished and etched samples were imaged under optical and SEM to characterize
defects such as the recast layer, microstructural changes, 
and heat-affected zones. The recast layer thickness was 
measured from SEM images. Microstructural effects such 
as grain size, grain distribution, and grain orientation in 
the recast layer were measured using SEM images. The 
standard linear intercept method was used to measure 
grain size. The rapid resolidification of material in the 
parent metal often leads to precipitation of secondary 
phases. Due to differences in the thermal expansion co-
efficient and lattice mismatch, the precipitation of

Table 4: Copper electrode in titanium parent material.

| Elements | Results (wt%) |
|----------|---------------|
| Cu       | 68.78%        |
| Al       | 22.15%        |
| Ti       | 3.62%         |
| Ca       | 3.05%         |
| K        | 1.73%         |
| V        | 0.672%        |

Note. In some trials, minor traces of Fe (0.063%) were obtained, but this was not consistent.
secondary phases often leads to formation of microcracks. Composition of the different regions in the recast layer and phases can be characterized using a combination of energy dispersive spectroscopy (EDS, an attachment to SEM) and X-ray diffraction analysis. The EDS report for the titanium parent material can be found in the Data Availability section of the report (Tables 4 and 5). An EDS report was not conducted on the Inconel parent material due to time and cost constraints.

### 4.1.1. Preparation of Postprocess Specimens

Many of the detrimental defects of EDM processes are at microscopic levels and need careful destructive sample preparation. It

![Figure 8: Mean $\mu$ due to cut depth in Inconel.](image8)

![Figure 9: Mean $\mu$ due to cut depth (a) and electrode diameter (b) in titanium.](image9)
becomes extremely important to make sure that new defects from specimen preparation are not introduced into the sample. First, specimens for microscopy were cut from the parent material workpiece specimens after electrode study cuts were made. Standard metallographic techniques [1] were used to prepare the samples [ASTM E3-11]. As most of the defects from EDM drilling are on nearby surfaces and hole walls, careful cross-sectional samples of the structures will be prepared using a custom low-speed, tungsten-carbide tipped cold saw blade. The samples with desired sections were mounted on Bakelite discs. Samples were carefully polished using a range of SiC polishing papers (with increasing fineness, i.e., mesh size from 200 to 1200 mesh), diamond polishing (1 μm diamond size), and microcloth (with silica/alumina slurry down to 0.5 μm). To reveal the microstructure of the metallic samples, further etching of specimens using etchants for high-temperature materials was performed. Suitable commercial etchants for high-temperature aerospace materials include Adler’s reagent. Due to the use of out-of-house processing for the SEM imaging, exact knowledge of the location of the magnified images (Figures 4(b)–4(d), 5(b), 5(c), 6(b), and 6(c)) is uncertain; however, these magnified images are contained within the low magnification images (Figures 4(a), 5(a), and 6(a)).

### 4.2. Microstructure and Defect Analysis of Inconel Specimens

#### 4.2.1. Electrode Wear Study

Figure 7 shows a schematic of the electrode wear SEM specimen and its origin relative to the cut parent material workpiece. It is important to realize that the “trench” is cut in the SEM.

The specimen is a cross-sectional view of electrode cylinder wall impact into the parent material.

Low magnification image (Figure 4(a)) shows nonuniform width of the machined trench (i.e., conical machined volume) in the parent Inconel material with smaller width at the bottom of the trench. The observation is likely due to wear of the copper alloy electrode at the tips during the EDM process.

The surface of the machined trench appears very rough and wavy with significant adhesion of molten debris/material on the machined surface (Figure 4(a)). It is well reported that sparks during EDM melt the workpiece [1]. The molten material is then ejected and flushed away. It appears that most of the debris on the surface are formed due to rapid quenching of the molten material by the coolant. It is also possible that the ejected molten material is redeposited on the surface.

A high magnification image (Figure 4(b)) shows the microstructure in the parent material and the deposited debris. The parent material exhibits typical microstructure of Inconel with coarse matrix grains with grain size in the range of about 25–75 μm and some precipitation, likely of MC carbides, at the grain boundaries. There exists a distinct/sharp boundary between the deposited material and the parent material. The deposited material shows lamellae of extremely fine dendritic/cellular grains, indicating rapid solidification of molten droplets as the source of formation. The grain boundaries appear cleaner in the deposited material likely due to dissolution of carbides in the melt. Microcracks are observed in the deposited (resolidified) material.

The microcracks appear to originate between the dendritic grains in the deposited material and reach the interface with some cracks reaching the grain boundaries of the parent material. Microporosity is also observed in the deposited material.

In addition to the deposited debris (Figure 4(b)), the parent material showed formation of the recast layer (Figures 4(c) and 4(d)). The recast layer has variable thickness along the length of the trench, with a thickness range of about 20–100 μm. The surface of the recast layer showed microcracks (Figure 4(c)). At some places, the cracks originated inside the recast layer and reached into the parent material at grain boundaries (Figure 4(d)). Note that grain boundaries in the parent material have hard precipitates and are highly susceptible to cracking. The recast layer exhibits highly refined dendritic/cellular grains characteristic of rapid solidification. In selected regions of the recast layer, some grains show distinctly differing contrast (i.e., dark and bright grains in Figure 4(d)). The differing grain contrast could be due to a distinctly different orientation or composition of the grains. It is possible that the wear and melting of the EDM electrode lead to incorporation of copper in the recast layer, thereby significantly altering the composition of the recast layer. In the MRO industry, this could compromise the parent material costing long lead times and high repair costs.

#### 4.2.2. Stud Removal Study

In the “Stud Removal Study,” the drill was used to remove a fastener from the parent material instead of directly cutting into the parent material. The low magnification image (Figure 5(a)) shows the damage to the parent material threads after EDM stud removal. A recast layer with thickness up to 100 μm is observed on the machined surface of the parent material.

At some regions, complete disintegration of the recast layer into fragments was observed (Figure 5(a)).

In the regions where the recast layer was still bonded, several defects were observed. For example, a large, trapped bubble in the recast layer can be clearly seen (Figure 5(b)). The vertical cracks in the recast layer reach the interface with the parent material.

As with other specimens, grains with a distinctly differing contrast were also observed in the recast layer of titanium alloy, indicating compositional modification.
$y = 0.0058x^2 - 0.0181x + 0.0848$

$R^2 = 1$

![Graph showing Electrode Wear Ratio vs. Cut Depth in Inconel.](image1)

**Figure 10:** Mean $\zeta$ due to cut depth in Inconel.

$y = -0.0238x^2 + 0.1435x - 0.1936$

$R^2 = 1$

![Graph showing Electrode Wear Ratio vs. Cut Depth in Titanium.](image2)

**Figure 11:** Mean $\zeta$ due to cut depth (a) and electrode size (b) in titanium.
possibly from incorporation of the electrode material in the recast layer or from compositional/grain texture effects (Figure 5(c)). Extensive horizontal cracking inside the recast layer was also observed, which is shown in the next section.

4.3. Microstructure and Defect Analysis of Titanium Alloy Specimens

4.3.1. Electrode Wear Study. A low magnification image (Figure 6(a)) shows the EDM machined trench in titanium alloy. The width of the machined trench is relatively uniform. The machined surface is relatively rough and covered with the recast layer. Compared to Inconel specimens, the cracking of the recast layer in the titanium alloy sample was extensive. The fracture and delamination of the recast layer can be clearly seen near the base of the machined trench. The recast layer with a thickness of up to 50 μm was observed. It consisted of refined dendritic/cellulargrains consistent with the rapid solidification molten material of the workpiece (Figure 6(b)). The rapid resolidification occurs in multiple layers due to ejection and flushing of molten material as the EDM machining progresses, resulting in distinct layers of dendritic structure in the recast layer. The orientation of dendrite growth also changes in the resolidified layer indicating complex phenomena related to heat flow and melt flow dynamics.

At many regions, the recast layer is extensively cracked (Figure 6(c)). Both vertical through-thickness cracks and lateral interfacial cracks were observed, causing disintegration of the recast layer from the parent material. The cracks in this recast layer are potentially harmful to the parent material if the material were under high stress or temperature for long durations.

4.3.2. Stud Removal Study. A stud removal study of titanium specimens was not completed due to the lack of on-hand electrodes and the high cost of purchasing more electrodes for the study. Future studies could focus on stud removals from titanium parent material.

4.4. Electrode Study Results. The repeatability results from the electrode study are included here. The material characterization results from this study are shown in the next section. The results presented in this section are intended to identify correlations among cut depth, electrode diameter, and parent material on electrode wear, potentially informing decisions related to repair design and supply chain management.

4.4.1. Material Removal Rate (μ). Table 6 shows working material removed over cut time, as shown in equation (2). Results are shown in Figures 8 and 9, revealing evidence of predictable behavior in relation to cut depth in Inconel, which is likely due to the higher thermal conductivity of Inconel. This is not the case when considering the results from titanium, as there is no apparent evidence of

| Task | Mean (mL/hr) | Standard deviation (mL/hr) | Relative standard deviation (%) |
|------|--------------|---------------------------|-------------------------------|
| 1.1  | 11.8         | 0.206                     | 2                             |
| 1.2  | 10.8         | 0.283                     | 3                             |
| 1.3  | 9.52         | 0.209                     | 2                             |
| 2.1  | 7.78         | 3.42                      | 44                            |
| 2.2  | 8.51         | 0.562                     | 7                             |
| 2.3  | 7.24         | 1.64                      | 23                            |
| 3    | 12.7         | 1.52                      | 12                            |
| 4    | 10.6         | 2.38                      | 22                            |

\[
y = 0.0265x^2 - 0.0275x + 0.0938
\]

\[R^2 = 1\]
predictable behavior. To develop a prediction model for titanium, further investigation is required.

4.4.2. Electrode Wear Ratio ($\xi$). Table 7 shows volume (from mass and density) change comparison between the working material and the electrode, as shown in equation (3). Results are shown in Figures 10 and 11, revealing better predictability with Inconel and a lower wear ratio with titanium. As observed in Figure 11, there was negative electrode wear on the shallowest cut depth. The result of apparent negative wear pointed towards the need for SEM image observation to characterize the consequences. The negative wear was observed to be the result of parent material depositing onto the electrode. Upon inspecting the SEM images, it was apparent that the electrode was also depositing material into the parent material. This is believed to cause the extreme variance in wear results. This mixing of materials could potentially have negative effects on parent material performance. Also, it was observed that more splatter occurred when cutting into titanium along with some parent material being deposited on the electrode, and this is believed to be caused by the lower conductivity of titanium, making the cut more difficult for the E-Drill™. This observation is consistent with an observation

![Image of electrode wear with cut depth in titanium.](image)

**Figure 13**: Mean $\xi_a$ due to cut depth (a) and electrode size (b) in titanium.

**Figure 14**: Variation in electrode wear with cut depth in titanium.

| Task | Mean   | Standard deviation | Relative standard deviation (%) |
|------|--------|--------------------|---------------------------------|
| 1.1  | 0.0711 | 0.207              | 292                             |
| 1.2  | 0.0761 | 0.0152             | 20                              |
| 1.3  | 0.0998 | 0.0249             | 25                              |
| 2.1  | −0.0498| 0.116              | 233                             |
| 2.2  | 0.0172 | 0.000594           | 3                               |
| 2.3  | 0.00740| 0.00643            | 87                              |
| 3    | 0.0517 | 0.0499             | 97                              |
| 4    | 0.00831| 0.112              | 1353                            |
in the next section. The large values for the standard deviation are due to two variables, cut depth and electrode diameter. The electrode diameter had the largest impact on the standard deviation values as can be seen in Table 7. This could be due to a number of factors, but, again, these cuts were made into the titanium parent material which has been shown to be less consistent than that of Inconel. Despite the large standard deviation value, it was necessary to draw conclusions from this because of the potential use in the MRO industry when dealing with smaller diameters.

4.4.3. Axial Electrode Wear ($\varepsilon_a$). Table 8 shows a change in electrode axial length during cut, as shown in equation (4). Results are shown in Figures 12 and 13, revealing reasonably predictable behavior, especially for Inconel. This behavior could once again be caused by the better thermal conductivity of Inconel. The amount of electrode wear appears to increase significantly more with increasing cut depth in Inconel than in titanium. Significant splatter in titanium accumulated on the electrode, as shown in Figure 14, which affects axial electrode wear measurement results.

5. Conclusions

In this study, the electrode wear characteristics and microstructure effects of a novel EDM hand drill were evaluated. This was to provide a foundation to determine if the electrode wear behavior is predictable and to build an understanding of what mechanisms are occurring at the microscale. When cutting into Inconel predictable behavior was observed. The material removal rate and electrode erosion were predictable, which produced consistent and intuitive trends. The electrode wear rate was more dependable in Inconel with increased cut depths of 2.54 mm and 3.81 mm such that the standard deviation was less than 25%. The material removal rate was even more predictable with standard deviations of less than 5%. This was not the same for cutting into titanium, such that the material removal rate and electrode erosion did not appear to follow any clear trend and thus are not likely predictable by these metrics. In some titanium cases, negative electrode wear was observed, meaning the electrode increased in length. This is caused by parent material deposition onto the electrode. This phenomenon was not observed in the Inconel experiments.

Variations in the severity and type of defects were observed in both titanium and Inconel specimens. The recast layer thickness was up to 100 $\mu$m in Inconel and 50 $\mu$m in titanium. Trapped air bubbles in the HAZ layer created a porous structure, leaving the material brittle. Notable amounts of microcracks form from the porous structure of the HAZ, and these cracks extend up to approximately 100 $\mu$m in length and in some instances crossed the HAZ/parent material interface. Large deposits of electrode material were observed and can be seen mixing with the parent material.

In the titanium specimen, multiple layers of dendritic grains are observed. This is indicative of rapid melting and solidification during the EDM process. These defects can have significant implications in material performance, possibly reducing component performance below acceptable standards if proper measures are not taken.

Findings from this paper show the viability of a hole drilling EDM for aerospace and industrial uses when removing fasteners. New knowledge obtained from this study includes that (1) the electrode wear rate and material removal rate can be predicted for Inconel better than for titanium, (2) there is deposition of parent material on the electrode and electrode material in the workpiece, and (3) microstructure defects in the HAZ layer include air bubbles with microcracks in Inconel and multiple layers of dendritic grains in titanium. The implications of this study for general use include potential prediction of the electrode wear rate for supply chain management purposes, prediction of the material removal rate for process time planning, possible compromise to workpiece material strength and corrosion properties after fastener removal, and the likely detrimental effect on fatigue properties due to microcracks and grain structure.

Data Availability

Materials are available, and data are available upon reasonable request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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