PLASMA ETCHING TO HELP IDENTIFY ACOUSTIC AGGLOMERATION SOOT PATTERNS ON SMOKE DETECTOR PIEZO DISKS

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ABSTRACT

The examination of soot in acoustic agglomeration patterns on smoke detectors has been used by forensic investigators to determine whether or not a piezo disk horn in a smoke detector sounded during a fire. This analysis is based on theories developed by the German physicist, Ernst Chladni. Chladni's vibration patterns of sand on a metal plate mimic the acoustic agglomeration patterns of soot on a piezo disk. While these patterns are useful, they must first be visualized. Such visualization is clearly evident on a smoke detector that has little soot deposits but can be unclear and sometimes impossible to see on detectors that are heavily sooted. Plasma etching is a quick process, causing cleaning of soot at a 1.5 microgram per second rate. It is a gentle cleaning method that differs from the traditional cleaning methods such as ultrasonic baths and wire brush techniques that would completely clean a piezo disk leaving no soot residue behind. This plasma etching process allows the user to remove the carbon soot in micrometer increments, until finally the acoustic agglomeration pattern(s), if any, can be visualized.

BACKGROUND

In a perfect scenario, fire investigators will recover a smoke detector from a fire scene that is minimally damaged. The investigator will then try to determine if the detector was sounding during the fire by looking at the localized area around the horn as well as the piezo disk itself. If the piezo disk horn was sounding during the fire, a concentration of soot would accumulate on and around the piezo disk in the form of acoustic agglomeration patterns. In the case where the working detector succumbs to the fire and ceases operation, soot will continue to accumulate on the piezo disk and detector, covering the layer of acoustic soot agglomeration with a uniform layer of soot deposits. The issue then becomes how to definitively identify acoustic soot agglomeration patterns on smoke detectors that have heavy soot deposits.

To tackle this issue, research has been carried out on sooted smoke detectors by using plasma etching as a means to remove micron layers of soot deposits. For this research, working detectors were placed in fire atmospheres where they were allowed to sound and collect acoustic soot agglomeration patterns. The same detectors were then de-energized and reintroduced to the fire atmosphere to the point that the previous soot patterns were obscured by the formation of a new uniform layer of soot. Investigators need a procedure for removing this uniform layer of soot without damaging the possible acoustic soot agglomeration patterns that lie beneath. For this, the sooted piezo disks are placed in a vacuum chamber with diatomic oxygen present. An RF field of 13.56 MHz is then introduced into the chamber such that a glow discharge of plasma develops. The effects of the vacuum and RF are such that the O_2 disassociates into monoatomic oxygen. The monoatomic oxygen then combines with the atomic particles of soot, forming carbon monoxide, carbon dioxide, and ash. The vacuum pump subsequently removes these waste products from the chamber.

The purpose of this study is to produce a *proof of concept* for the use of plasma as a means to delicately remove soot deposits from piezo disks found in the alarm horns of smoke detectors. It examines the usefulness of plasma etching technology in helping distinguish the acoustic agglomeration patterns on piezo disks with heavy soot deposits. The different situations examined in the study are soot accumulation on a disabled (not working) smoke detector compared to the soot accumulation on an enabled (working) smoke detector.

EQUIPMENT

A material was needed to provide dark, heavy soot when burned. It was also desired to use a material commonly found in households. Memory foam mattresses are becoming more common, and memory foam is mainly made up of polyurethane. It is known that polyurethane does not combust completely, thus generating soot particles and microdroplets of condensed organic vapor into the air. These particles are primarily carbonaceous, meaning they contain mainly carbon. For this study, an IKEA Sultan memory foam mattress was used as the sole fuel source of the fire and soot. The mattress was cut up into 2”x2”x2” cubes.

A PE-50 Plasma Cleaner was used to uniformly clean off thin layers of soot until the acoustic agglomeration patterns on the piezo disks could be seen. Oxygen was used as the gas during this reaction.

A Lecia MZ 75 optical microscope was used to identify patterns in soot agglomeration on the piezo disks. Under the microscope, subtle differences would stand out when determining if patterns were formed on the piezo disks. This microscope was also used to gather microscopic pictures for data purposes.

A Sartorius Semi-Micro balance scale was used to measure the weight of the soot removed during the plasma cleaning process. The scale had a resolution of 0.00001 grams and was calibrated prior to testing.

Figure 1 – PE-50 Plasma Etch

DISCUSSION

Enhanced Acoustic Agglomeration on the outside of an un-melted detector

In a perfect scenario, fire investigators will get a smoke detector that has not been physically damaged in the fire. In this scenario, it is possible to tell if the alarm was sounding at the time of fire just by looking at the area around the horn slits. Figure 2 below shows what this will look like. These are two of the same model smoke detectors that were subjected to smoke at the same time in the smoke tower.

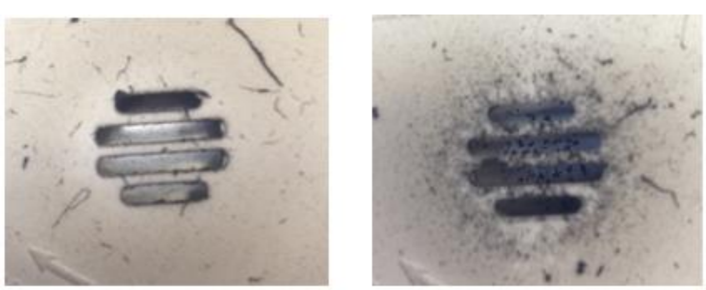


Figure 2 - (Left) Disabled smoke detector. (Right) Enabled smoke detector.

There is a clear difference between the two horn slits and the immediate area around them. The detector on the left is showing basic soot coverage around the horn slits. There is a slight buildup of soot concentrated on the 90-degree edges where the horn slits start. The detector on the right shows a concentrated build-up of soot around the horn slits. The pattern of enhanced acoustic soot agglomeration on the outside of the detector is in the form of normal soot lines.

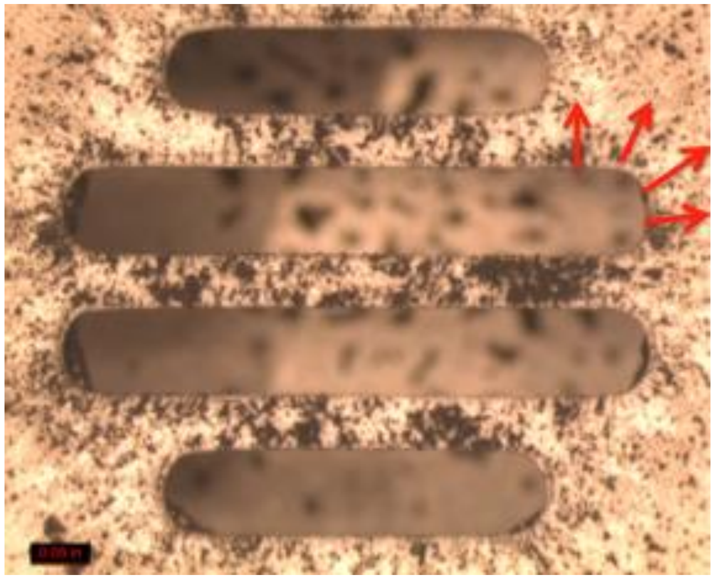


Figure 3 – Normal Soot Lines

Concentrated soot collection due to sharp angles

During this study, a certain phenomenon was observed through various tests. In some cases where the soot was extremely dense and thick, there would be a more concentrated patch of soot near sharp edges and ridged lines.

Figure 4 to the right, shows this phenomenon. The sharp edges around the "TEST" button on the smoke detector collect generous amounts of soot particles. This is due to the airflow flowing through the smoke detector with soot particles. The air combined with soot particles flows over the smoke detector, but when the air flows through the sharp 90-degree turn, heavier soot particle get caught on the edge creating a buildup. For clarity, figure 4 shows a smoke detector that was disabled during the fire. This detector was not sounding during the fire. Figure 5 below shows another example of concentrations of soot deposits on ridged edges. The detector on the left was disabled and did not sound during the fire. The detector on the right was enabled and did sound during the fire. The detector on the left does not show the normal soot lines seen in the right detector. The left detector should not be mistaken as an alarm that sounded.

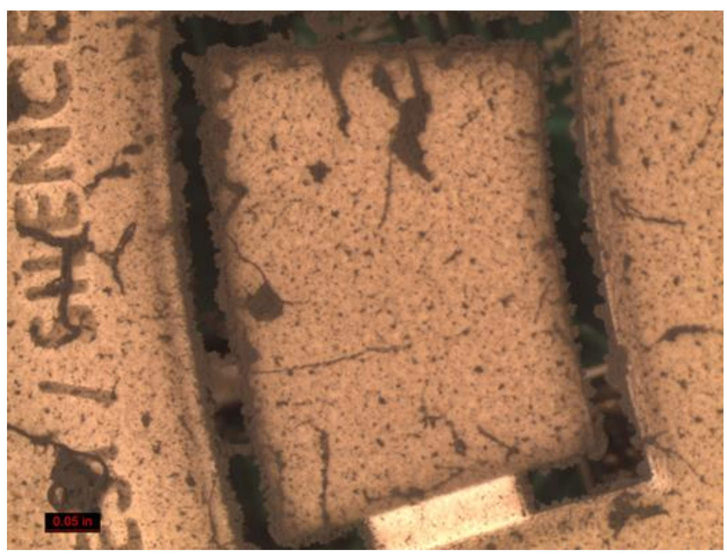


Figure 4 – Soot buildup on sharp edges

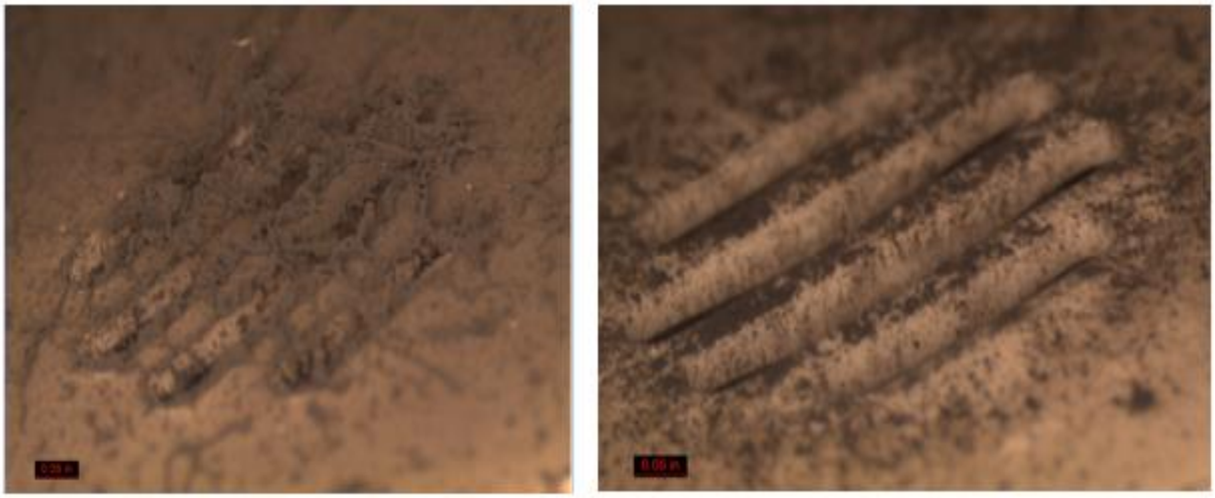


Figure 5 – (Left) Soot deposits on disabled smoke detector. (Right) Soot deposits on enabled smoke detector.

Acoustic agglomeration patterns on piezo disks

In the previous section, the smoke detectors were not damaged by fire. This made it possible to view the soot deposits on the outside of the detectors to look for acoustic agglomeration patterns. When the outer polymer case is damaged, it is extremely difficult and sometimes impossible to determine if the alarm was sounding at the time of the fire.

Figure 6 – Smoke detectors that were damaged during the fire.

For this scenario, our scope turns to the metal piezo disk located within the smoke detector. There will be enhanced acoustic agglomeration patterns on this component as well. Figure 7 below shows microscopic views of piezo disks subjected to soot. The left picture shows a disk with basic uniform soot deposits. The disk in the left picture was disabled and did not sound during the fire. The right picture shows a disk with acoustic agglomeration patterns. There is a clear difference in soot concentration patterns. The sounding disk causes the soot particles to group in small symmetric concentrations. These concentrations look similar to crystals, but they are made out of soot.

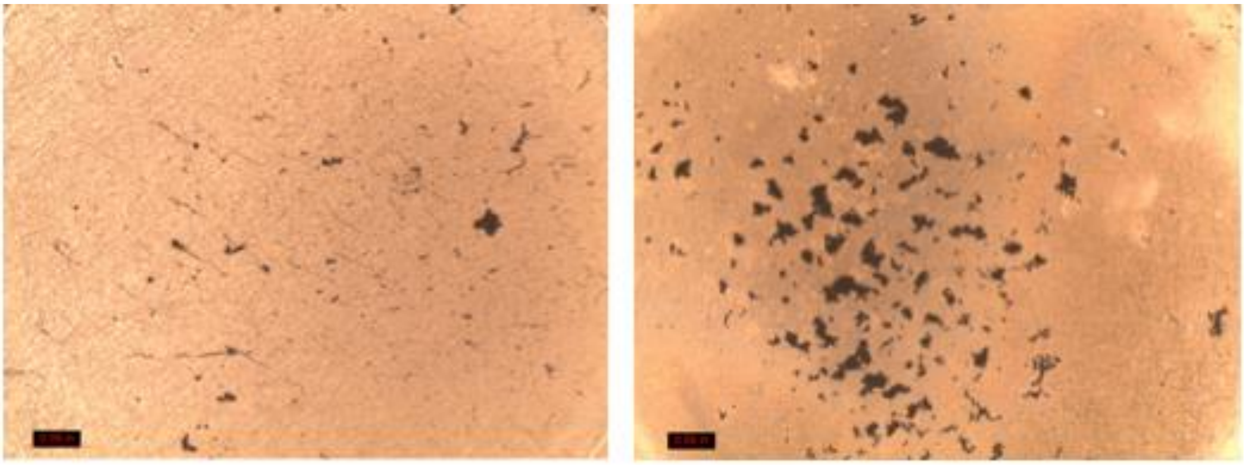


Figure 7 – (Left) Piezo disk of disabled smoke detector. (Right) Piezo disk of enabled smoke detector.

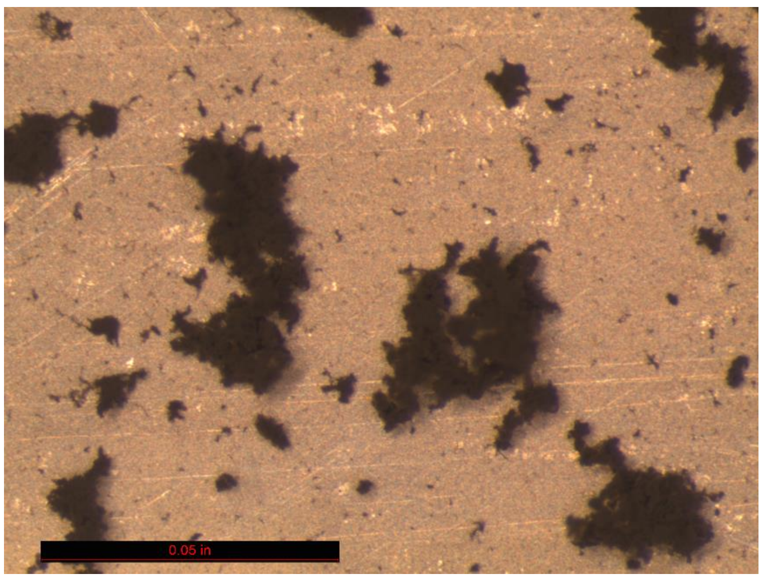


Figure 8 – Microscopic view of Soot Crystals.

Figure 8 above is a microscopic view of the right photo in Figure 7. These “soot crystals” are very distinctive. There will not be any evidence of these on a disk that was not sounding during the fire. The disk with basic soot deposits will have random lines of collected soot, and there will be a uniform distribution of soot over the whole surface of the disk.

PLASMA ETCHING

Taking the scenario one step further, there are some cases where the alarm has sounded during the fire, the soot collects on the disk in an acoustic agglomeration pattern, the fire continues and the smoke detector is damaged enough to where the alarm stops sounding, and a uniform layer of soot deposits over the soot crystals formed earlier when the alarm was sounding.

To simulate this, the smoke detectors were smoked for a period of time where the alarm was sounding, then the battery was removed, and the detector was subjected to soot again. As shown below in Figure 9, the two disks are similar enough in patterns to increase the possibility of false positives and false negatives.

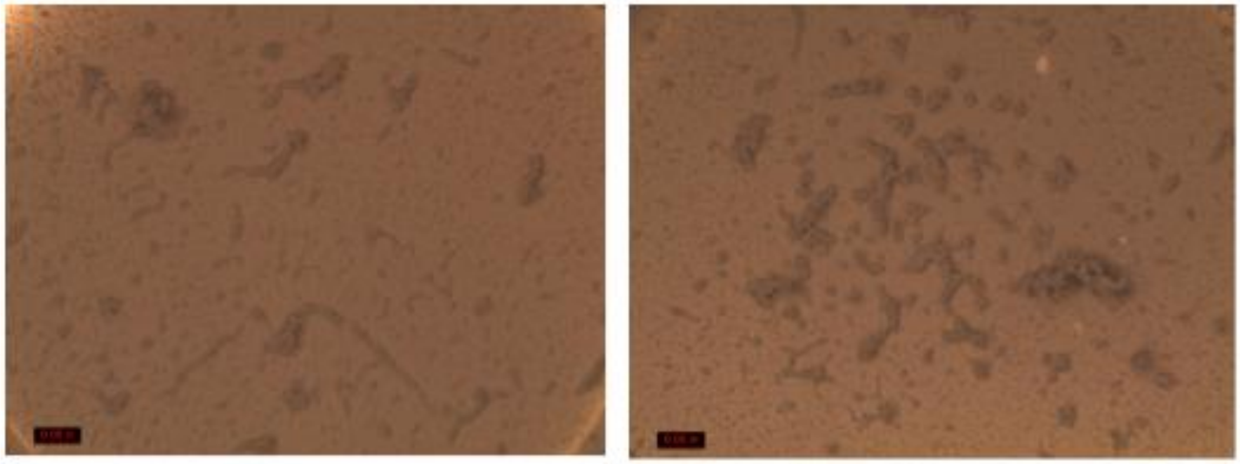


Figure 9 – (Left) Piezo disk of disabled smoke detector. (Right) Piezo disk of enabled smoke detector.

To return to the initial soot layer, a plasma cleaner was used to take off the top layer of soot. This will allow the most important layer, the layer of soot deposited at the beginning of the fire, to be viewed. The process is illustrated below.

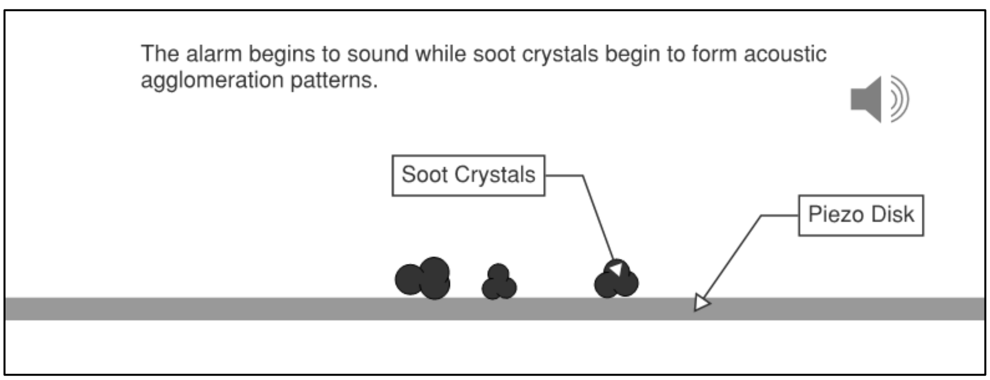


Figure 10 – Initial formation of Soot Crystals on an enabled piezo disk.

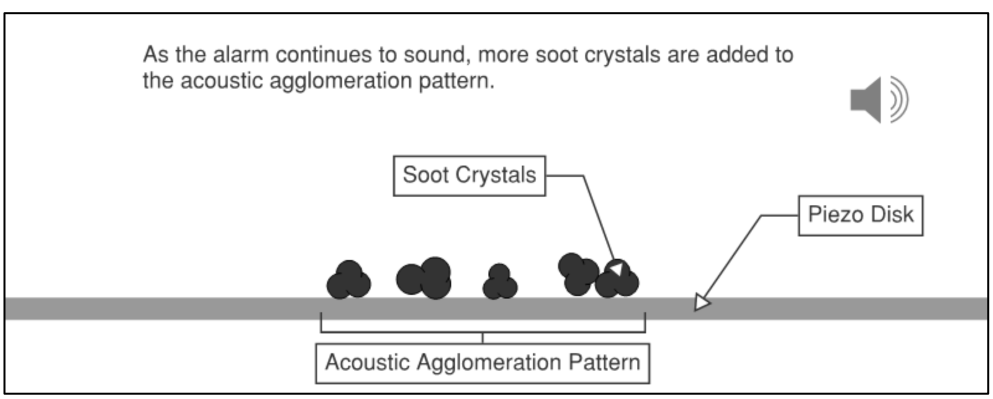


Figure 11 – Continued formation of Soot Crystals on an enabled piezo disk.

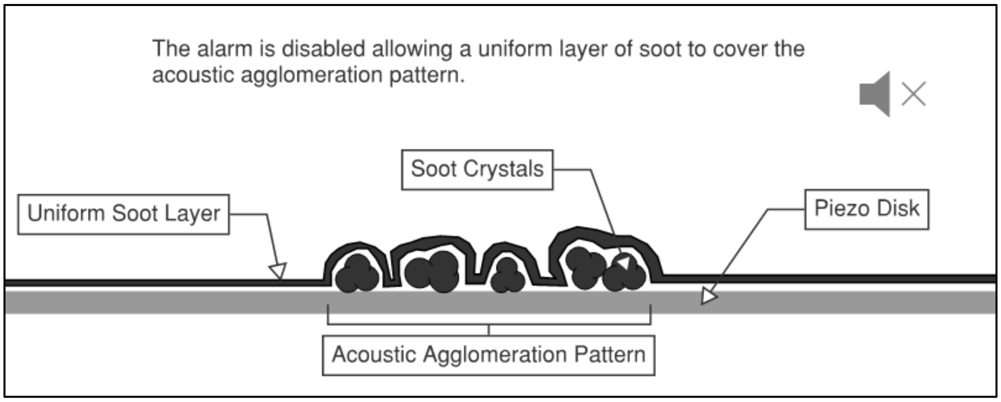


Figure 12 – Formation of uniform soot layer on a disabled piezo disk.

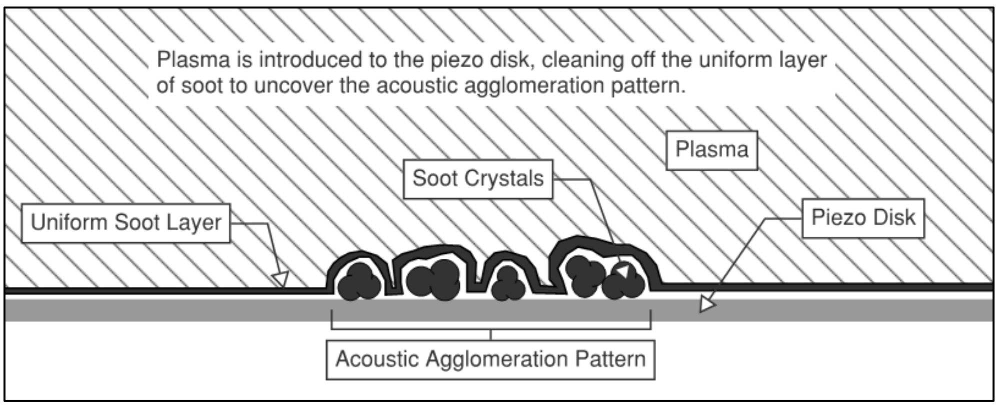


Figure 13 – Piezo disk introduced to plasma.

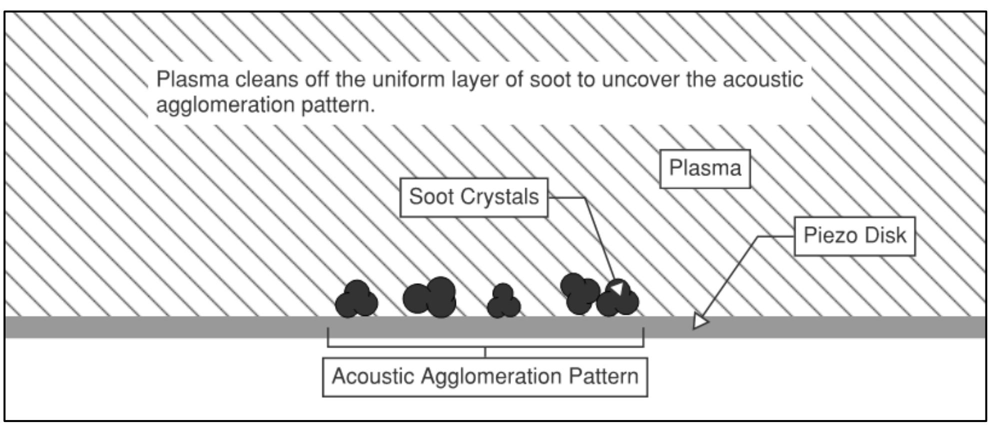
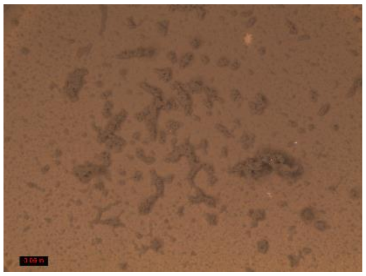
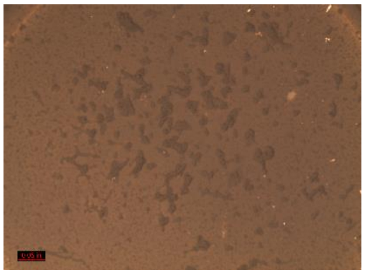


Figure 14 – Removal of uniform soot layer covering the acoustic agglomeration pattern.

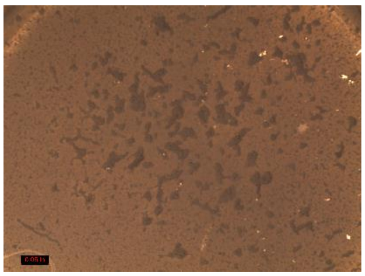
PLASMA ETCHING RESULTS



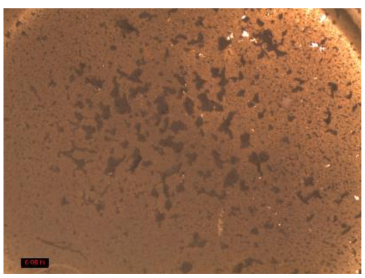
To the left is a piezo disk that previously sounded during a fire. The alarm was then disabled, and the disk was reintroduced to soot. A uniform layer of soot recovered the disk preventing a clear visualization of any enhanced acoustic agglomeration.



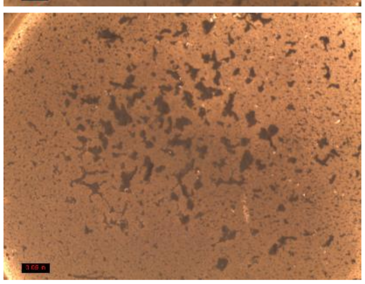
The disk was put into a PE-50 Plasma Etch machine. This is a picture of the disk after 1 minute of plasma cleaning.



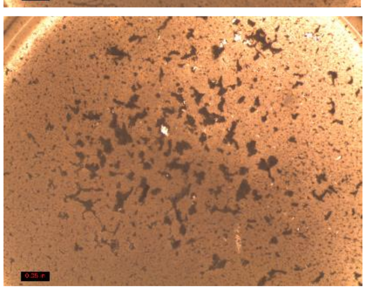
Disk after 2 minutes of plasma cleaning.



Disk after 3 minutes of plasma cleaning.



Disk after 4 minutes of plasma cleaning.



Disk after 5 minutes of plasma cleaning.

The weight of soot removed after each minute of plasma etching varied between tests. The average rate of soot removal was 1.5 micrograms per second. It was found that the weight of soot removed after each minute decreased exponentially after each minute of cleaning. The acoustic agglomeration pattern on the piezo disk after 5 minutes of cleaning was significantly easier to recognize.

Can Plasma Etching Cause A False Positive?

Could plasma cleaning a piezo disk that was disabled during a fire cause the disk to mimic acoustic agglomeration patterns? Disabled disks were cleaned. Figure 14 shows a progression of plasma cleaning on a disabled disk.

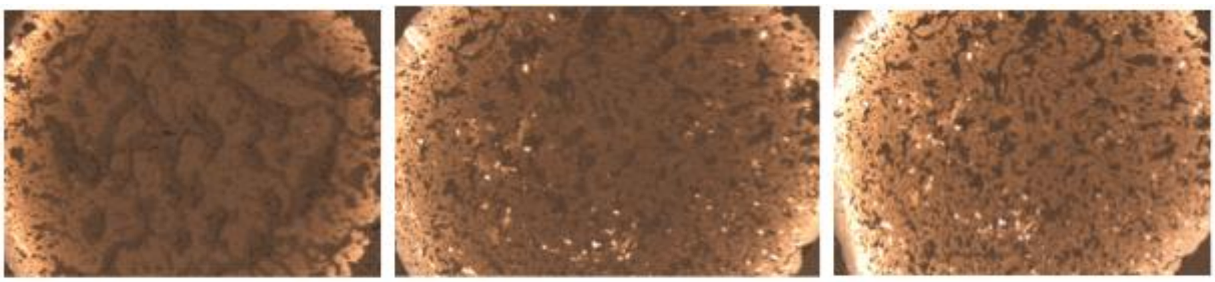


Figure 15 – (Left) Disabled disk reintroduced to soot. (Middle) Disk after 1 minute of plasma cleaning. (Right) Disk after 2 minutes of plasma cleaning.

From Figure 15 above, the right picture is the 2-minute plasma cleaned disk that did not sound during the fire. When compared to a plasma clean disk that was sounding during the fire, the differences become very evident. Figure 16 below shows this comparison.

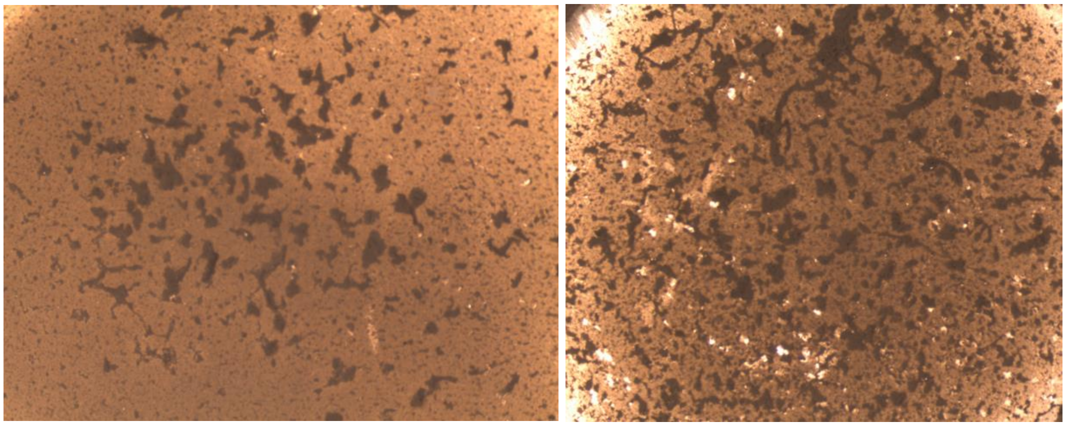


Figure 16 – (Left) Enabled piezo disk, plasma cleaned. (Right) Disabled piezo disk, plasma cleaned.

CONCLUSION

When determining if a smoke detector was sounding during a fire, there are key things to look for. One out of the three generally needs to be found to be able to determine that the alarm was sounding during the fire.

1. Normal soot lines protruding outward from the horn slits along the surface of the detector. These lines will be obvious to the naked eye and even more evident under a microscope. The lines will be defined as lines normal (perpendicular to the tangent line) to the edge of the horn slits. It is important to distinguish the difference between normal lines forming and soot build-up along the sharp edges of the horn slits.

2. Normal soot lines protruding outward from the hole on the horn housing faceplate. These are the same lines found on the horn slits. If the design and geometry of the internal components of the smoke detector prevent normal lines forming on the horn slits, the normal lines will form on the horn housing faceplate below the horn slits.

3. Soot crystals forming on the piezo disk that accumulate in a symmetric pattern. If the alarm is sounding in the presence of soot, the soot will collect in patterns on the metal piezo disk. The formations will be consistent with the pictures in this report. It is important to know the difference between the soot crystals forming in a symmetric pattern on the disk or spread out among the entire disk area in no obvious pattern.

The use of plasma etching was shown to enhance the view of soot acoustic agglomeration patterns by removing the outer most layer of soot. The plasma cleaner uses monatomic oxygen ions to remove carbon content from the surface of objects in a uniform manner. The soot, being rich in carbon content, is strongly affected by this method of cleaning. The operator must be conscious of the elapsed time because leaving the piezo disk in the plasma cleaner for too long will produce a sparkling clean disk. A safe method of cleaning requires the disk is only subjected to plasma cleaning 1 minute at a time. Remove the disk after 1 minute and inspect the disk to determine if another minute of cleaning is required. The objective of using plasma to clean the outer most layer of soot is because the plasma is gentle enough not to damage the acoustic agglomeration patterns that lie below. This method will aid in the inspection of smoke detectors and could ultimately help answer the question: Was the smoke detector sounding during the fire?

ABOUT THE AUTHORS

William Steward: A degreed Mechanical Engineer that received his BSME from Texas A&M University in 2016 and is currently the Lab Manager at Goodson Engineering located in Denton, TX. Mr. Steward is responsible for operating and maintaining laboratory instruments at Goodson Engineering. He also performs research for the firm and assists in investigations.

Mark Goodson, PE: An Electrical Engineer that received his BSEE from Texas A&M in 1979 and is licensed to practice engineering in numerous states, and is licensed both in EE and ME. After engineering school, he attended UT Southwestern (Dallas) in a forensic medicine track. He was the first PE to serve on the State of Texas Electrical Board. From 1989 to 1991, he served as a Court Special Master. He is the PE selected to sit on the Texas State Fire Marshal Science Advisory Workgroup, SAW. He was a member of the Editorial Review Board for the *Fire & Arson Investigator*. Mr. Goodson is the principal in the firm Goodson Engineering of Denton, Texas. He holds 14 patents and has 15 more pending. He is a member of the NIST OSAC, serving on the Fire Sciences panel. He sits on the Board of Directors (PPAC) of the US Patent Office. He has published 36 peer reviewed technical articles, with 30 of them dealing with fire science. He has published in the Forensic Sciences Investigator, *Journal of Forensic Sciences*, *American Journal of Forensic Patholog*y, and the *Forensic Sciences Gazette*. Mr. Goodson serves as a consultant to many Medical Examiners' Offices in Texas.