INMM 2018 – Baltimore, Maryland

Title: Active Tamper Detection for Secure Enclosures

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Abstract:

Where an organization is trying to protect sensitive equipment, it is common to use lockable/sealable enclosures to limit access to this equipment to those with the necessary access clearance to do so. Such enclosures are typically secured with locking/sealing mechanisms, while some higher security enclosures may be designed to passively show tampering on their surfaces and/or locking/sealing mechanisms. While this might be acceptable if the enclosure is located within the organization's controlled buildings, it becomes more problematic for organizations like the International Atomic Energy Agency that installs a variety of unattended monitoring and measurement systems protected in enclosures in facilities around the world. Similarly, the US Department of Homeland Security utilizes secure enclosures exposed at border crossings and ports of entry throughout the world. This paper will discuss a new way to manufacture enclosures with active tamper monitoring. The paper will review the motivation to create active tamper monitoring systems and evaluate a range of potential approaches such that enclosures can actively detect tampering, record and locate such an event, and where practical, report the tampering back to the home organization. The design of a prototype active enclosure material will be outlined. As a work in progress, current status and future plans will be discussed.

Introduction:

What is the safeguards and border monitoring problem(s) being addressed?

Secure enclosures are critical tools for the International Atomic Energy Agency (IAEA) to execute its safeguards mission. The IAEA uses a variety of passive and active seals to secure containers for the transfer, storage and operation of safeguards relevant equipment and materials. In most all cases, these seals only provide one-point protection, on the door or lid of the enclosure.

The digital domain has opened up many deployed systems to potential cyber-physical attack vectors and this risk is more acute when the adversary has physical access to computer systems. This is particularly true of enclosure systems that are not under the full control of the owners. The IAEA uses tamper resistant enclosures to house unattended monitoring systems and critical electronics that are located in the potential adversary's "house."

Most enclosures use passive tamper indication including externally applied seals and paint with a color and texture that is difficult to accurately replicate is scratched or damaged. Some enclosures have a door switch (that triggers whenever the door to the enclosure is opened) to

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detect authorized and unauthorized access. Other methods to resist tampering include approaches such as internal hinges on access doors, internal anti-pry bars on these doors that interlock with the upper and lower frames upon closure, and the use of internal frames to support external panels eliminating any mounting connectors on the outside of the enclosure. These are just few examples of typical tamper detection and resistance approaches.

However, both passive and active measures have their drawbacks. Passive measures rely on in-person inspections to identify tampering. It may be necessary to utilize non-destructive evaluation (NDE) techniques during an inspection in order to detect tampering of enclosure walls and this can be cumbersome and time-consuming. It is frequently impractical to inspect all of the external and internal surfaces of an enclosure as doing so would require near complete removal of enclosed equipment. On the other hand, the seals that are currently used only protect one point of access to a container/enclosure. A door switch can only detect tampering should an adversary choose to access the enclosure through this door by opening it and if this switch is connected to or transmitted to a central alarm station. But that remains a highly unlikely path for a sophisticated adversary. With data acquisition systems typically controlled using a computer or at least communicating through an Ethernet port, unauthorized access to any port can bring the entire system under the control of the adversary. Many deployed systems are not able to report status in real time or near real time.

Examples of enclosure-based systems that are not in continuous control of the authority include, for example, radiation-based detection systems at border crossings that are not manned 24 hours a day 365 days-a-year and International Atomic Energy Agency (IAEA) Unattended Monitoring Systems (UMS) and Surveillance (optical) Monitoring Systems (SMS) that are installed in nuclear facilities. Of these two domains, the IAEA systems that are installed in the potential adversary's facility are at the highest risk. Risks are further exacerbated by the use of remote data transmission back to the IAEA, which while being an important cost saving measure, also means large intervals in time between visits to these enclosures. This means that even a blatant and obvious breech of a passive tamper detection system cannot be detected until the next visual inspection that could be significantly removed from the original tamper event. Even visual inspection might not reveal such a breech if there is enough time to conduct a careful repair of the external entry point or if it is merely obscured by the extensive installed equipment that deny visual access to the interior surfaces of the enclosure panels.

To address these threats PNNL has explored the use of next generation containment systems with active tamper detection that can be remotely monitored and verified. This technology has the potential to modernize the labor-intensive processes for in-situ verification of continuity of knowledge. In the future, verification will benefit from the use of smarter, highly networked, and *active* secure materials directly embedded in strategic assets in order to enable real-time remote verification and tracking. Current verification with NDE is limited to what can be measured by inspectors during on-site visits, whereas smart materials could assess both surfaces and internal conditions of hard to reach areas. This research addresses needs described in: the IAEA's 2018 Research and Development Plan and the Development and Implementation Support Programme for Nuclear Verification 2018—2019. It also addresses the Department of Homeland Security Cyber Security Strategy.

Secure enclosure with active nervous system to detect, record, and report tampering

Approach:

To enable these developments, PNNL has researched the technical requirements for active secure enclosures. We have conducted a review of sensors to determine which would be suitable for inclusion and researched ways to make sensors integral to the design and function of the enclosure. One way to build next generation enclosures with embedded sensors is to use additive manufacturing (AM). Recent developments in AM research have sparked a wave of innovation in manufacturing because building objects layer by layer can produce shapes that cannot be made by traditional methods, it can dramatically reduce manufacturing costs, it can eliminate waste, and it offers the ability to rapidly produce, test and improve new designs. AM with metals is a particularly active area of research owing to applications in automotive, aerospace, and many other fields. Selective laser sintering (SLS) is the most popular AM method for metals, but the high-temperature process and reliance on fine metallic powders has led to some difficulties with controlling defects and material properties that ultimately determine a part's performance. Additively manufacturing a secure enclosure would require the use of metals, but high-temperature laser sintering processes are not conducive to inclusion of sensors.

Instead, our research has focused on a promising sub-category of additive manufacturing (AM) called ultrasonic consolidation (UC). This type of AM allows bonding of metal sheets at relatively low temperature [1-6]. UC utilizes sound waves and pressure to induce a solid state bond between layers of metal foils [3]. When combined with precision milling equipment UC can be used to build up 3D objects in solid metal into complex structures. In contrast to typical metal 3D printing methods (like SLS) UC typically operates at temperatures that are low enough (~100 °C) to allow inclusion of sensors and other materials that would otherwise be damaged [7, 8]. One of the unique features of UC is the ability to bond dissimilar metals [9, 10]. UC is commonly used with aluminum, copper, gold, iron, magnesium, molybdenum, nickel, platinum, silver, titanium, tungsten, and many alloys of these. Many pairs of these metals have been proven for successful UC bonding. This allows for the ability to make novel composite materials with unique properties.

Our research has focused on two areas: 1) improving fundamental understanding of the ultrasonic consolidation process to ensure quality outcomes[11], and 2) Designing prototype objects with embedded sensors to test their effectiveness at laboratory bench scale. UC has unique abilities and advantages that are not currently utilized for international safeguards or border monitoring system. However, there are barriers to the adoption of this technology. Unfortunately, no model exists to predict optimal process parameters for ultrasonic consolidation. This is especially true when there is a complex combination of materials, changing part geometry, and embedded components[12]. The process parameters are typically optimized in an iterative fashion each time. This means that the process must be adjusted and tested for each new layer in a 3D part. Inspections can be performed on a layer-by-layer basis in order to assure quality outcomes; however, this slows the process significantly. Post-process inspection of a whole part is also often needed. Measurements of the process *in situ* could help ensure that the metal-to-metal interfaces are strongly bonded and not “over-welded”, which could damage embedded sensors or “under-welded”, which could result in layer separation. It could also be used to accurately predict parameters as the UC process progresses.

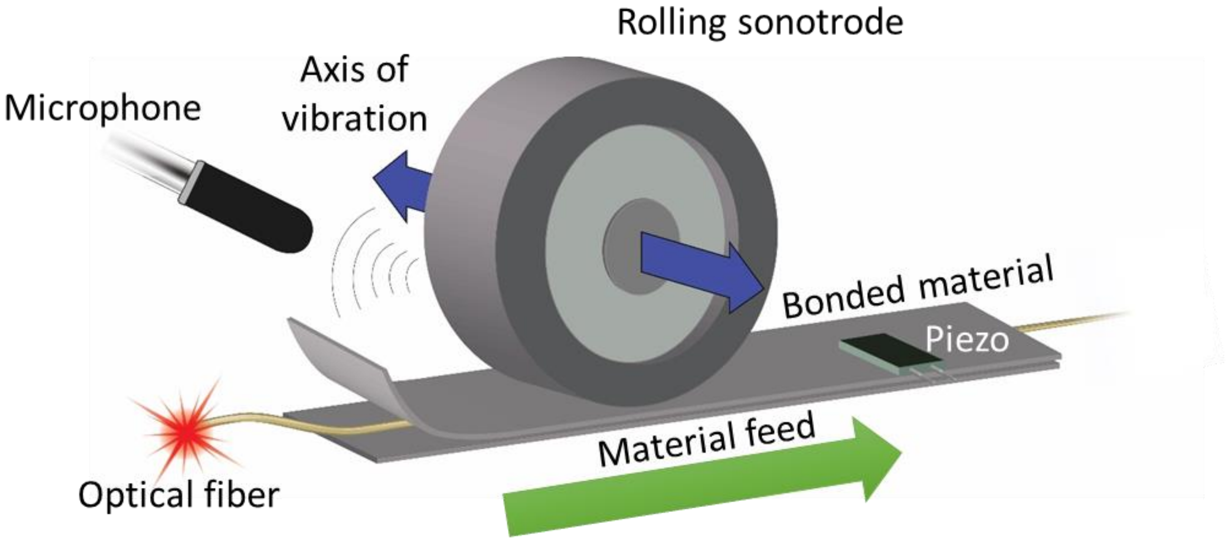

Figure 1: Conceptual illustration of how UC works, showing how stock material is fed into the rolling sonotrode. Sensors can be inserted between layers for embedding, such as the optical fiber and piezoelectric sensors shown here. External sensors such as microphones can be used to monitor the process externally to ensure quality outcomes.

<ins>Current results and discussion</ins>:

We chose a selection of sensors that are compatible with the UC process to embed during laboratory tests. Sensors were chosen for the greatest possible crossover utility in terms of process monitoring while the component is being made and for long term utility as a health and tamper monitoring sensor. We also aimed to choose complementary sensors that do not rely on the same physical stimulus. This enables independent orthogonal verification to increase confidence in readings. For example, it will be important in a real world scenario to minimize false positive alarms. Multiple overlapping sensors have the best chance to do this. Facility environments can be very complex and challenging. With this work we are aiming to determine which combinations are viable and which combinations result in the most secure final system. Table 1 shows a list of sensors that can be embedded in an enclosure's wall and that can be used for external process monitoring while that enclosure is manufactured.

Table 1: Advantages and trade-offs of various sensor types as they apply to embedded measurements in 3DUC.

Sensor	Capabilities and limitations
Embedded sensors	
Optical fiber	**Pro**: Measures vibration and strain. High temporal resolution. Infinitely configurable. **Con**: Very sensitive to noise. Requires light source.
Piezo	**Pro**: Measures vibration passively. **Con**: Very delicate sensor.
Thermocouple	**Pro**: Measures temperature changes, such as those caused by wasted energy. **Con**: Slow temporal response. Data comes from one location.
External sensors	
Acoustic	**Pro**: Non-contact. Simple instrumentation. **Con**: Sensitive to instrument background emissions. Not viable for field use
Piezo	**Pro**: Not sensitive to background acoustics. **Con**: Contact required. No spatially resolved data.
Thermal Imaging	**Pro**: Non-contact. Good spatial information. **Con**: Heated area is not immediately visible. Imaging systems are expensive and slow. May not be viable for field use
High-speed video	**Pro**: Visual confirmation of sonotrode and sample oscillations. **Con**: Cameras at 20 kHz are expensive. Limited spatial resolution. Not currently viable for field use

Active sensor examples:

Optical fiber sensor: Optical fibers are a preferred option for health monitoring because they are known to be very sensitive to strain and can be added to relatively large structures such as bridges at a reasonable cost. For this reason, they may also be used to monitor UC and detect tampering. We aimed to observe the ultrasonic vibrations occurring during a UC process through a fiber that was being embedded in aluminum. A 125 µm single-mode silica fiber

(SMF-28 from Corning) was sandwiched between two Al layers. A third layer was cut in half and was used as a spacer, leaving a small channel for the fiber. A diode laser was shined in one end of the fiber while a high speed silicon photodetector collected light on the other end. The signal was recorded on an oscilloscope while the whole piece was bonded with a bench scale ultrasonic bonding machine. The photodetector signal shown in Figure 2 clearly shows high frequency modulation that is consistent with the ultrasonic vibrations from the welder. This is a preliminary result, but it indicates that data from an embedded sensor can be collected during the manufacturing process.

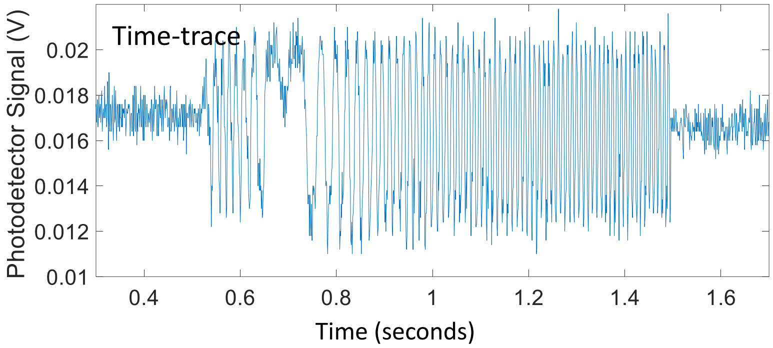

Figure 2: Time trace of high-frequency intensity modulation of fiber throughput due to welder vibrations. The fiber is embedded within 3 aluminum foil layers and is directly under the sonotrode during the welding process.

Piezoelectric sensor: Polymer (PVDF) films are low cost, flexible piezoelectric sensors. Using an approach similar to that described for optical fibers, piezo films (purchased from SparkFun) were bonded between layers of Al. The sensor generates a small voltage when it is compressed so it can detect touches, vibrations, and movements associated with tampering. High-frequency voltage signals were recorded using an oscilloscope and are seen in Figure 3. It is likely that what we recorded here is the excitation of the sensor's resonance frequency, and we observe it shifting as the material undergoes compression and – possibly – degradation.

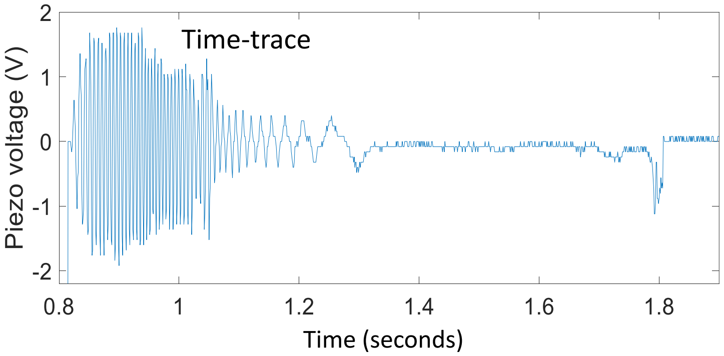

Figure 3: Vibration data taken from a piezo sensor embedded between layers of Al. The time trace shows the vibration collected during a weld.

Acoustic microphones: Calibrated high dynamic range acoustic microphones were used to collect the sound emissions during the UC process. The sensors were external to the manufactured part and were most useful for monitoring the process for quality outcomes. Microphones were positioned 2-4 inches from the metal-joining sonotrode. A benefit of collecting acoustic data during the manufacturing process is that it could be used in a feedback loop to correct poor joining parameters during the manufacturing process. Figure 4 shows a characteristic time trace of the audio data and two Fourier Transfer spectrograms. The data indicate that it may be possible to distinguish between a good joining process and an unsuccessful one. This would provide a sort of real-time monitoring of quality during manufacturing. When the joining was not successful it could be repeated with adjusted parameters.

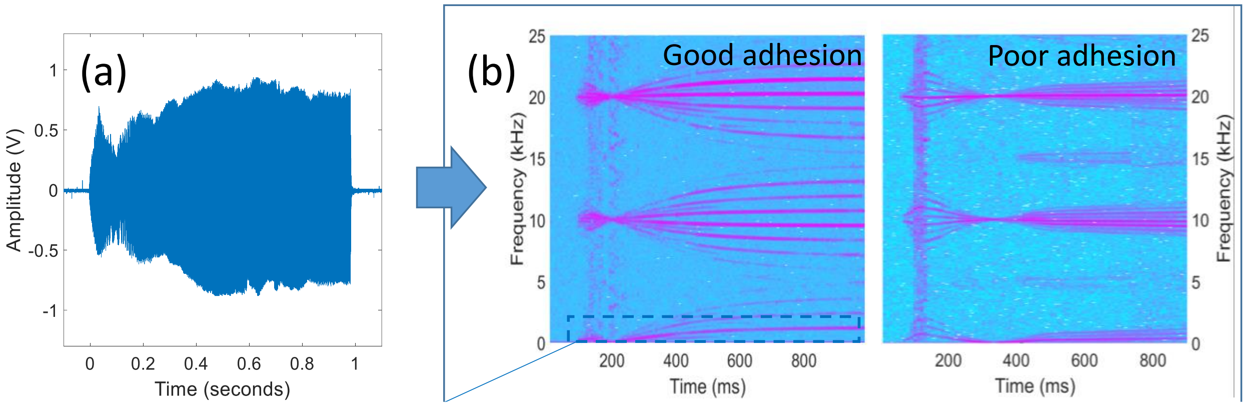

Figure 4. Demonstration of typical acoustic data recorded during 1-second welds on Al foils. Data is recorded as a time-trace (a) and then converted to spectrograms to analyze spectral features (b). Differences are highly noticeable when the Al foils are fixed (b-left) versus when they are allowed to slip against each other (b-right). Within the low-frequency striation patterns fine features appear which may be useful for understanding weld quality and comparing against other sensor data. Within the first 300 msec of each weld interesting differences are observable between strong and weak bonds that may prove important.

Design of a small-scale prototype with embedded sensors:

The UC process has the ability to make large parts so it would be reasonable to scale up to large enclosures, similar in size to the ones used by the IAEA in their unattended monitoring systems and border control measurement systems. In this effort, we have focused on a smaller scale prototype in order to demonstrate the strengths and differences of making active structures with UC. The design, shown in Figure 5, will include several embedded sensors. This prototype will be about the size of a smartphone when it is completed in the summer of 2018 by Fabrisonic, LLC, which is a partner in our effort. There are several prominent features that are designed to enhance the object's security. First, the barcode on the surface of the part reveals the composite structure of the underlying metal. UC can easily bond dissimilar materials so we integrated alternating layers of copper and aluminum. Selectively cutting away the first layer of aluminum will reveal a bar code in the first layer of copper. The barcode on the surface will match the pattern in the alternating layers that make up the solid metal of the whole object (seen at the front edge). Effectively, the identifying barcode is integral to the whole structure of the object. The second prominent feature is the snaking pattern of optical fiber that is revealed in a cutaway on the right side of the object. The fibers will be critical for tamper-monitoring. The layout of the fibers was carefully selected to accommodate the limited turn radius of the fiber while maintaining a high density for maximum security. If an adversary attempted to drill through the surface it would either break the fiber or the vibrations would be detected in the fiber. The front edge has spaces for piezoelectric sensors. Power and computing resources will be placed in a recessed space beneath the part. When complete this object will be tested for tamper detection. For example, we will attempt to drill through the object while measuring data through the multiple sensors. We will also test the object to determine how robust and reliable embedded sensors are in varied environments and demanding conditions.

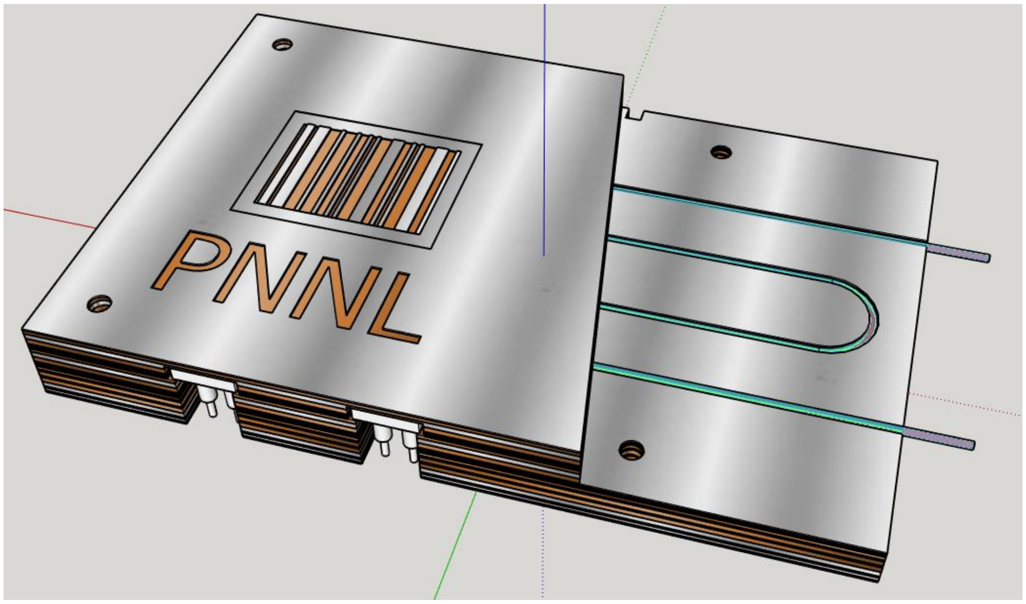

Figure 5: Drawing of a prototype part with embedded sensors that is currently being built.

<u>Conclusions</u>:

This paper has presented a new way to make solid metal materials with embedded sensors using a promising sub-category of additive manufacturing – ultrasonic consolidation. This technology has applications in domestic national security activities and international safeguards because it could be used to make active tamper-indicating enclosures. As an example, smart enclosures with embedded sensors could dramatically reduce the need for on-site inspections if the enclosure could self-verify and report. Likewise, smart containers could reduce the need to inspect containers in high risk environments. However, further study of smart materials in the context of safeguards is needed to determine the costs, benefits, and prerequisites for the IAEA as well as boarder control systems to develop and implement this technology. The research is part of a recently started project and is ongoing. Future plans include the manufacture of a prototype part, testing of the prototype in varied conditions and eventually scaling up the design and processes presented here so they can be used to make full scale active tamper-indicating enclosures in the future. More research is also needed to better understand ultrasonic consolidation and better monitor the manufacturing process *in situ* to ensure quality outcomes.

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Acknowledgements:

This research was performed at Pacific Northwest National Laboratories (PNNL), which is operated for the DOE by Battelle under contract DE AC06-76RLO 1830. The work was supported by the Laboratory Directed Research and Development (LDRD) program. Funding was also provided by the U.S. Department of State's Key Verification Assets Fund (V Fund).

The authors wish to acknowledge Jacob Benz for reviewing the manuscript.