A PRELIMINARY EXPLORATION APPLICATIONS OF SMART/PRO-ACTIVE MATERIALS IN 21ST CENTURY SHEILDED NUCLEAR FACILITY

ABSTRACT

Today's growth of technology across many fields of engineering is rapid and progressive, however, the field of Nuclear Power has been delayed in its response. The existing technology developed in the early 1990's makes the construction and operating cost of current hot cells excessive, their design is conservative with large, thick concrete structures that are not designed for Post Operational Clean Out (POCO) and decommissioning.

This paper outlines examples of smart material technology, their current applications and the developing ideas which have the potential to heavily decrease contamination needs of a nuclear shielded facility. It explains in detail the research carried out and discusses the feasibility of each possibility. The report focusses on exploring the possibilities of analysing smart materials such as super hydrophobic or sensitive surface finishes for future hot cells.

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1 INTRODUCTION

'Hot Cell' is the industry term for a shielded nuclear containment cell. The hot cell is dedicated to processing radioactive nuclear materials and protects operators and the general public from radiological and other hazards while conducting the first step of disposal. Existing Hot Cells comprise of thick reinforced concrete structures with sophisticated ventilation and containment systems to provide the required protection.

The current model of hot cells used across the industry incur high operational costs and were rarely built with POCO and decommissioning at the forefront of design. Current industry practice is to use austenitic stainless steel cladding on all exposed surfaces inside the hot cell that may become contaminated. The surface allows the area to be remotely cleaned using devices controlled by operators viewing through small lead glass windows (Fig.1), however there is the inherent risk of oversights with surface defects making it difficult to thoroughly decontaminate the chamber.

Fig. 1 Operator remotely controlling equipment through shielded window

This** method has been practical for the past 60 years since the beginning of nuclear technology. The rapid growth in technology over the last 10 years has introduced many new materials and surface treatments that could prove practical in improving safety and lowering costs throughout the nuclear sector.

This report will discuss research into a range of applications of smart/pro-active materials such as super hydrophobic and sensitive materials, some of which are in use in the food and pharmaceutical sectors. After exploring the above, a number of recommendations will determine if the applications are viable within a nuclear hot cell and what further actions and testing should be undertaken.

2 OBJECTIVES

The outcome of this research paper is to improve safety throughout the life cycle of a nuclear hot cell by utilising smart surfaces/materials. To reduce, or even totally eliminate contamination, the fundamentals are to allow the unwanted material (liquids, sludge etc.) to easily be moved across any surface within the chamber it may contact. Any material remaining after the completed processes will be easily removed. Ideally, to make the surface 'self-cleaning', the contact angle between the unwanted substance and the surface itself needs to be increased so the substance will not stick. A contact angle greater than 150° is considered a super hydrophobic surface (Fig. 2) i.e. repellent of water based materials or super omniphobic if it repels materials with a low surface tension.

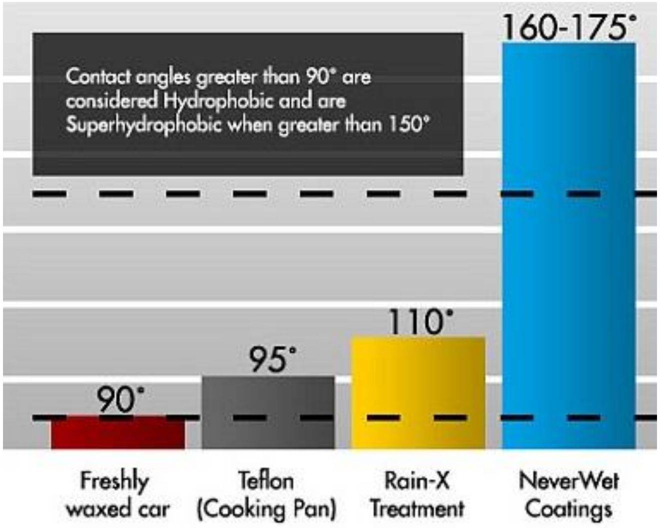

Fig.2 Degrees of hydrophobicity [*]

Creating a surface finish like this would allow efficient cleaning of the system. This paper will include research into smart surfaces that resist liquids and will conclude a range of possibilities that fulfill the above objectives.

3 RESISTANT COATINGS

In the advance of smart materials one of the most researched concepts is resistant materials. Taking inspiration from the lotus leaf (*Nelumbo genus*) and its ability to repel water so easily, commercial spray-on coatings have been developed that are super hydrophobic.

The products generally require two procedures to make surfaces[1] have a hydrophobic finish. The base application plus a number of top coats followed by a curing time of approximately 12 hours to form a frosted film. This film can be easily removed once operations are completed, leaving behind a clean surface in the hot cell. During operations, any liquid will travel over the surface with only a small applied force required to overcome frictional forces. Any spillages on surfaces with an

[1] wood, metal and plastics are considered most appropriate.

angle greater than 10° will mean the liquid will collect in a common sump from which it can easily be accesed by Remotely Operated Vehicle (ROV) cleaning equipment.

3.1 COMMERCIAL PRODUCTS

NeverWet (1) and Ultra-EverDry (2) are two products that are commercially available. NeverWet claims to apply a thin, almost clear coating that protects many surfaces including wood, metals and most plastics from wetting. Ultra-EverDry is a nanotech coating that is both super-hydrophobic and oleophobic (hydrocarbon repellent).

NeverWet is simple to apply in a ventallated area through a nozzle, the coating is also simple to reapply when the finish had deteriorated or lost its smart properties. However, in a consumer review (3) it was said that, “NeverWet often protected some part of an item but not the whole thing, and not for long.” The coating was uneven and, although protected the majority of the surface, some areas were left exposed. It was also vulnerable to abrasives causing coating removal and scratches. This means if the surface was to be used continuously the hydrophobicity would decrease rapidly.

Ultra-EverDry must be applied in a well ventilated environment, where respiratory equipment along with skin and eye protection is required. In a hot cell it would be relatively simple to remotely apply the coating that is specific to the inner wall material, be it plastic, steel, carbon fibre etc. In a online review (4), various potential objects were tested and the coating failed in its longevity however it was said that “Its industrial and commercial applications are a lot broader” as the testing was completed mostly on household products.

Although both names suggest the product will endure, neither are considered suitably durable for constant use and must be frequently reapplied.

Finally, there is a patent dated in 2014 for a “highly durable super hydrophobic transparent coating for glass, metal, and plastic that is manually dispensed” (5). The patent describes the need for an improved coating for the reasons as above. Although it is not said when their coating will become commercially available, there are procedures in place for testing.

4 INTRINSIC ALTERATIONS

For a surface to become self-cleaning, material must be unable to stick to it. One way, is for it to be hydro- or omniphobic. This is reliant on two things, its intrinsic chemical structure and its surface roughness. If both exist, the surface becomes super hydro- or omniphobic.

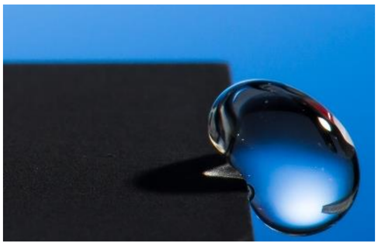

Fig. 3- Laser etched surface repelling water (7)

By creating nano/microstructures on the surface of a metal using a laser, a university in Rochester, New York developed an extremely water repellent surface (Fig.3). In their paper (6) “The multifunctional surface is useful for water/dust repelling.” In an interview, Professor Chunlei Guo states “the structures created by our laser on the metals are intrinsically part of the material surface.” (7) This means, unlike the spray on coatings, the effect will be more durable with an even ability across all of the surfaces. Once implemented, any spillages can be easily dealt with as any dust or small particular matter, that would otherwise be difficult to remove, can be handled easily.

Currently the optics laboratory at Rochester University, are developing surface etching that could be applicable to not just stainless steel but other materials such as plastics and carbon-composites.

Other research laboratories are developing similar surfaces with the intrinsic properties capable of resisting any material. MIT’s Department of Chemical Engineering uses a method of acid etching that produces a super hydrophobic metal able to withstand high temperatures (8). After contacting a postdoctoral candidate managing the testing, it was documented that although the process is harsh, the coating is uniform enabling it to work well on an inner surface of a tubular section.

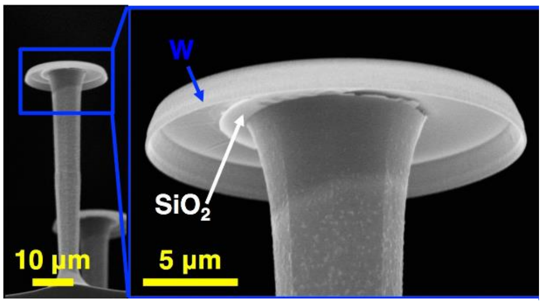

Fig. 4 Doubly re-entrant surface

A similar technique was discussed in Science Magazine (9). It creates micro-structures on the surface of silica and after testing several methods, the most effective structure was similar to an umbrella. The Net Forces on the liquids was dependent on the angle of the walls of the structure. When water droplets are in contact with the ‘doubly re-entrant structures with an upward slope’, (as seen in Fig. 4), the net force was in an upward direction (Fig. 5). This suspension of the usually wetting material (one that lacks an ability to maintain contact with a solid surface (10)) allows it to minimise the contact. It is not only hydrophobic but also omniphobic, meaning that even materials with low surface tension are repelled by the surface. The cushion it rests on makes it easy to brush away. Again the surface structures are not permanent and the application technique means it is more difficult to repair.

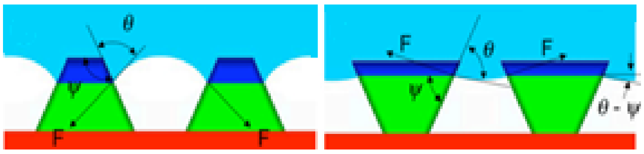

Fig. 5 Downward slope of structure (Left) and upward slope (right) give opposing net forces (F) (8)

4.1 PTFE

PTFE or its more common name Teflon [R], is a hydrophobic, readily available substance that has various forms and techniques of application including tape, powder and spray. Focussing on its indefinite life span, PTFE's increased durability even with vigorous use is a commercially available hydrophobic/resistant surface. The top layer is non-stick and can withstand high temperature and harsh conditions. Although its abilities are lower than the methods stated above, Teflon is tried and tested in many industries including oil and gas, UV and other radiation environments.

The flexible coating can be applied to polymer substrates such as rubber and elastomers and also to other temperature sensitive materials such as plastics, glass and carbon fibre (11). Teflon can also be applied to stainless steel as commonly demonstrated on kitchen cookware.

5 BASE MATERIAL

Existing systems typically use 304L grade stainless steel as the surface allows for better cleanliness. As the above research has shown, there are many materials on the market and in development that are more efficient at system cleaning. These surfaces and coatings can be applied to steel but often have further benefits when coating other materials.

Rogers Yacht Design (12) specialise in carbon fibre. Carbon fibre is a stiff material with a high tensile strength that is flexible before curing and can be moulded into complex geometries. Layers of carbon fibre fabric are aligned together to make a strong, durable surface that is resilient under heavy impact because of its high ultimate tensile strength (~3000MPa). The alignment of the fibres through the layering allows stress to be dissipated through the component. This can be used to reinforce specific areas and decrease the strength of others.

During an informative meeting with Rogers Yacht Design, an example of a carbon composite component that had been vacuum moulded was presented. The curved shape had been lacquered to a smooth, gloss finish with a small sheet of copper embedded along with a fibre optic sensor and a female threaded fastener insert incorporated into the structure without compromising the surface finish. Rogers explained that any type of smart sensor or joint feature could be set within the surface and many finishes including PTFE or other can be applied.

6 OUTLOOK AND SUMMARY

To address the problems with current hot cell design, more specifically the clean-up after operations, research was undertaken into various methods of smart surfaces and finishes. There is a lot of focus on research being done into the longevity of highly resistant materials. In an article written for the Royal Society of Chemistry (13) in 2013, Xue and Ma's paper reflects on what is being done to 'prolong the lifetime of super hydrophobic surfaces so that the materials can be used practically'. Currently, the Technology Redness Level of much of the research is quite low and the commercial products that are highly resistant are not suitable for harsh environments such as often experienced in nuclear hot cells. However the paper, written in 2013, is hopeful that large scale testing over the upcoming years will prove productive.

The super hydrophobic coatings are easily repairable but are currently inadequate for application within the type of environment of a nuclear hot cell. The highly hydrophobic finish can be wiped away which benefits POCO and decommissioning but also implies that it wears away easily. In spray form, it is quickly applied but may not produce an even coating. This was proved in testing where the coating was thinner on the outer edges of the component and also on other random areas making the coating less effective. Many of the concurrent research sources suggest that there are now more durable methods of production; this may be made commercial in the next few years.

Intrinsic modifications increase durability and effectiveness of the resistant property. There are different surface types, all of which create an air layer beneath the liquid to successfully repel it. The most successful method demonstrated by the University of Rochester, New York, is the engineering of repellent surfaces using laser etching. This process creates a durable, highly resistant surface that retains 30% of its kinetic energy when any liquid comes into contact. The lab oratory hopes to improve the surface properties further and promises technology of the future.

PTFE is a successful commercially available product. The non-stick surface is only hydrophobic and there for liquid will sit at a lower contact angle (typically 90°) than a super hydrophobic surface meaning more force is needed to move waste across it. However liquid will not stick to a PTFE coated surface even under high temperatures and harsh environments. It has different methods of application and can be coated on many materials.

To check all systems within the hot cell are functioning as desired and that surfaces are fully clean after operations, sensors can be placed inside the chamber. Setting these technologies on top of the surface will create gaps, increasing chances of contamination around the area. However, carbon fibre has an advantage where by sensors, other technologies and joint features etc. can be embedded in the highly tensile layers of the material without infringement on the smooth surface. This surface can be coated with most substances to make it resistant while still retaining its smooth shape.

7 RECOMMENDATIONS

Ideally all surfaces within the hot cell are to be SMART with finishes that are resistant to contamination. There is exciting opportunities for further exploration into the advance of resistive materials with benefits, the highlights being documented above. For a hot cell to be a smart system, knowing where the 'hot' spots are and the most appropriate methods are implemented to deal with any problems requires a holistic system approach.

The current marketable solutions (2015) are the established use of PTFE which can be flexible to mould onto any shaped surface and the spray coatings that make metals, plastics and glass highly hydrophobic. The latter are not durable, give an uneven finish and need to be re-coated often.

However, with the current research into advancing material engineering there is a strong belief that the laser etching technique will be able to be applied to other more flexible materials. This layered over a moulded carbon fibre shell for example with embedded sensor technology will allow a surface to detect when an unwanted substance is touching it. The surface or component can then send a relevant message to the ROV equipment within the cell that can transfer the material away for disposal. The alignment of the carbon fibres means that loads can be dissipated through the component. During POCO and decommissioning, it is suggested that the areas at weaker points can be forced to break, collapsing the shell within. The layer over the carbon fibre should be an etched surface. With any surface greater than an angle of ~10°, liquids and sludge will collect in a common area. This can be cleared easily, leaving no material behind as a result of the forces involved. With robotic technology, the etched surfaces could be replicated and repaired within the chamber.

Should these technologies not become commercially available then PTFE (Teflon) could be considered as a strong substitute. It is not as omniphobic, but is very resistant and non-stick. Material will be able to be cleared with relative ease and the embedded technology can detect any defects atop the PTFE.

A combination of the above will mean any intersections within the modular nuclear hot cell structure will be easy make even. This would include between modules and around equipment; it will also allow the system to work concurrently with itself to effectively clean up. This will reduce any contamination issues during an active period and allow for a more POCO when the Hot Cell reaches the end of its operational life.

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