Advanced materials for self-healing electrical insulation systems

S. Basu, I. German, R. Rhodes, G.C. Stevens, J. Thomas

Gnosys Global Ltd., 17-18 Frederick Sanger Road, The Surrey Research Park
Guildford, Surrey, GU2 7YD, United Kingdom

ABSTRACT

When damaged self-healing materials are capable of restoring the pre-damage characteristics and function of the material. Such materials have great value for components and infrastructure assets which are extremely difficult or expensive to access, including underground and subsea cables, transformers, and generator stators. In these examples, a lack of feasible preventative maintenance allows minor defects to grow over the course of many years, to the point that asset integrity is compromised. Repairing or replacing a damaged asset is a time-consuming and expensive task, and further penalties may be imposed due to loss of service or environmental contamination.

Here, we present examples of materials that have demonstrated excellent potential at the laboratory scale, and will soon be entering large-scale trials prior to full deployment. We will also highlight instances where Gnosys has undertaken internal research in order to develop specialist materials to address specific applications.

Keywords: *Self-healing, power cables, energy infrastructure, sub-sea, transformers*

1. SELF HEALING MATERIALS

Self-healing materials when damaged are capable of undertaking a specific response to restore the original properties of the material (see Figure 1). Infrastructure assets utilising self-healing materials can be expected to possess greater durability and failure tolerance, which in turn leads to reduced failure rates and enhanced asset lifetimes.

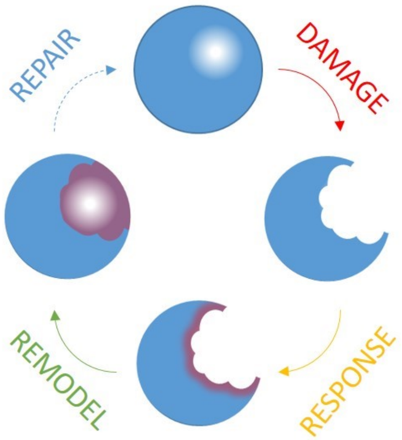

Figure 1. Conceptual repair cycle of self-healing material.

Although many assets would benefit from the capacity to self-repair, of particular interest here are those that are both high-value and difficult (if not impossbile) to access for inspection or maintainance. Without such intervention, minor defects can develop to the point that the asset itself is threatened. Once this state is reached, it is necessary to locate the damaged section of the asset, and either repair or replace it. If the component is an underground or off-shore cable, this process may take months to repair with costs frequently in excess of $2m [1]. Such defects can be introduced at any point from manufacturing to installation and throughout operation, and in some cases may be small enough (sub-millimetre) to evade detection, particularly in highly complex or very large assets. Figure 2 highlights examples of damage sustained by cables during manufacturing or laying, where scoring from sharp rocks or hand tools can frequently breach the outer sheath.

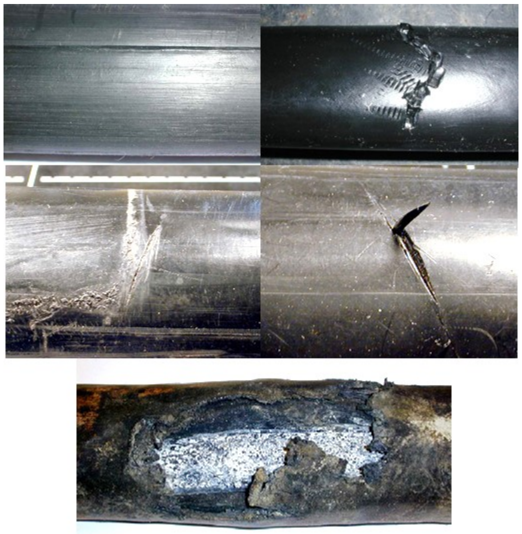

Figure 2. Examples of damaged cables from handling or scoring. The bottommost image shows a failed cable after 20 years of service.

While a large number of self-healing solutions have been developed, almost all can be separated into possessing ‘extrinsic’ or ‘intrinsic’ mechanisms. Materials that possess extrinsic self-healing properties rely upon fluid healing agents, dispersed throughout the material in hollow microstructures including spheres, needles, or complex vascular networks. When the material is damaged, these structures are broken and release the healing agent, which mixes and reacts to form a solid mass within the damaged region [2]. By comparison, materials that intrinsically self-heal incorporate labile and/or reformable bonds within the structure itself; if damaged, these bonds can reform and restore the polymer matrix (Figure 3) [3].

Both routes possess advantages and disadvantages that must be carefully weighed with respect to the application. Extrinsic systems are conceptually simple and can act reliably without an external stimuli (heat, light, etc.) but the repaired region is likely to be mechanically and chemically dissimilar to undamaged areas, which may make it a focal point for future failure events. Secondly, most intrinsic systems can only repair once; unless the system includes a complex vascular network, there is no means to resupply healing agents to an already healed area. In contrast, intrinsic systems can heal as many times as is necessary, and the properties of the healed region will ideally match undamaged regions. However, intrinsic systems generally require an external stimuli to start the healing process, and exposed surfaces quickly lose their capacity to heal, particularly in the presence of air and water.

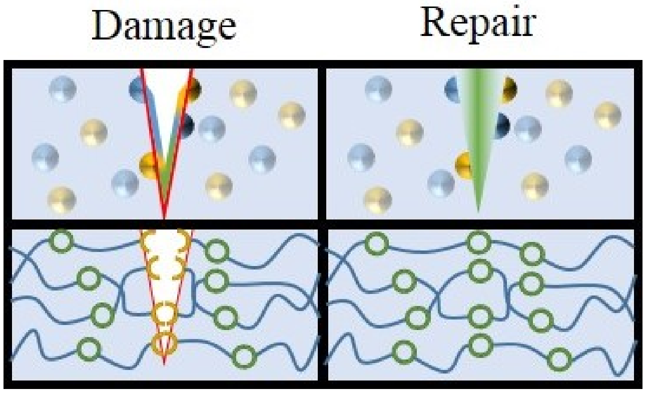

Figure 3. Schematic showing (top) extrinsic healing route and (bottom) intrinsic healing route.

A final approach involves the use of smart materials, which are capable of changing their morphology in response to a specific stimuli. Although these systems do not reform bonds or generate a permanent seal, the change in morphology can still be used to fill voids and carry out 'asset self-repair'. In this instance, the repair will generally remain as long as the stimuli is present; should this be removed, the material will revert to its original morphology and expose the damage once again.

2. SELF HEALING MATERIALS FOR POLYMERIC POWER CABLES

Within Europe and the USA, the use of underground cables (UGC) is becoming increasingly prevalent. Although their costs are substantially higher than overhead lines (OHL), they can be used in many areas where OHLs would either be unsuitable or unacceptable including sensitive and heavily urbanised regions. Many countries are committed to undergrounding the majority of new cabling, and the Netherlands has now completely undergrounded its electrical distribution network. Additionally, the growth of the low-carbon technologies including the rapid construction of off-shore wind has led to a substantial demand for off-shore cables. Compared to UGCs, offshore cables operate in extremely aggressive environments, and their location means that access is even more limited.

For UG and offshore cables, one of the greatest threats is water. While a completely sheathed cable is fully waterproof, if a small defect develops water can enter the cable and attack the insulation. The combination of water and high electrical fields generates intricate, dendritic structures known as 'water trees' (see Figure 4), which reduce the electrical breakdown strength of the insulation. If the ingress of water is not stopped, water trees can degrade the insulation to the point of electrical breakdown, resulting in cable failure. Water trees are also implicated in the formation of electrical trees, which can rapidly lead to the failure of the asset.

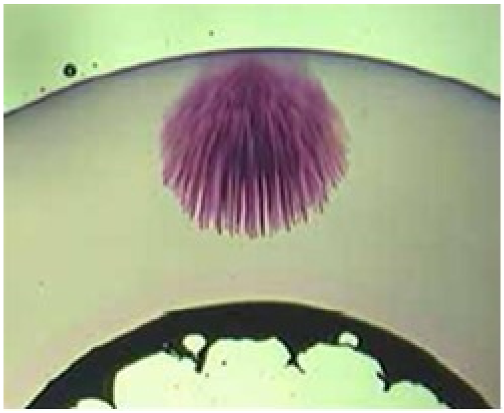

Figure 4. Water tree within cross-section of XLPE insulation. The water tree has been dyed to aid visualisation.

In order to prevent the formation of water trees, cable manufacturers currently utilise 'water blocking tapes' (WBTs), which can be wrapped at different points in the cable to prevent water ingress and migration. WBTs consist of two layers containing a layer of a highly swellable material such as poly(sodium acrylate) (PSA). In the event of water ingress, the PSA will swell and block the hole, thereby preventing further water damage.

Although WBTs represent the current industrial practice, investigations by Gnosys have found a number of problems with these materials. While WBTs possess a strong swell response, the PSA is not supported by surrounding layers and will swell to the point of dissolution, at which point the protective qualities are lost. The lack of mechanical support also means that pressurised water can force the PSA aside and directly penetrate the cable. These problems are exacerbated if the WBT is challenged with salt-water, as the high salt content limits the osmotic gradient and reduces the swell response. These latter points are of particular concern in offshore cables, where small defects can result in the ingress and explosive propagation of saltwater throughout the cable, largely unchallenged by the WBT.

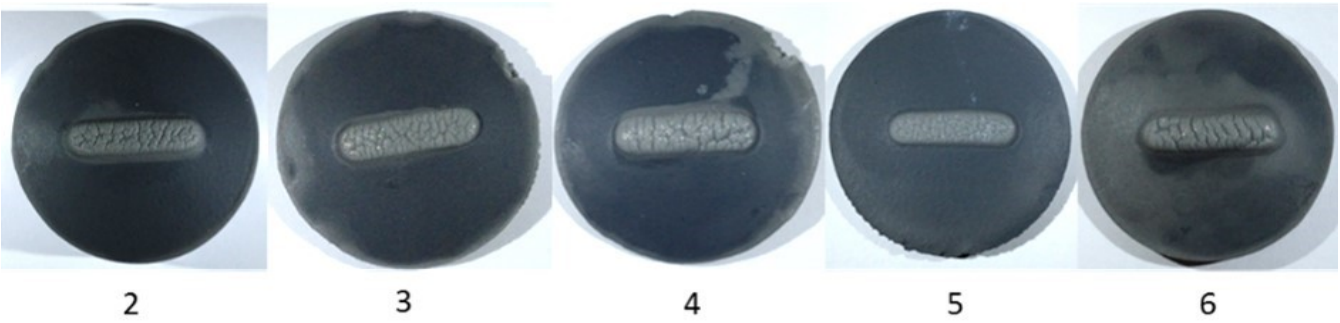

Figure 5. Samples of h-TPE tested under steadily increasing pressures (given in bar) with water ingressing through a 12x2 mm cross section defect in the centre of the disc. It can be seen that the h-TPE possesses a strong, stable swell response with minimal leakage even at high pressures.

As an alternative, we propose the use of hydrophilic thermoplastic elastomers (h-TPEs). While these utilise similar swelling additives, the TPE component confers a number of advantages. Primarily, the TPE provides mechanical support and constraint to the swelling additive. This mediates the swell response and also prevents the additive from dissolving ensuring that protection is maintained even when challenged with large volumes of water. This is particularly important when the damage region is subject to high water pressure, as shown in Figure 5, where the TPE provides sufficient reinforcement to allow successful swelling and blockage under conditions found to be untenable for WBTs.

Beyond the swell response, the TPE provides a second, highly efficient water blocking effect. Further, investigations have found that the TPE is highly compatible with common sheathing and bedding layer materials, and layers of h-TPE and sheathing form watertight seals when combined. As a result, the system is capable of preventing water ingress even in the presence of salt-water, where the swell response may be reduced. These additional capabilities suggest that these materials are suitable for offshore applications, and to date have demonstrated effective salt-water blocking at pressures equivalent to 65 m of seawater.

Beyond the water blocking capabilities of the material, we have also examined its processability. Commonly, WBTs are incorporated into a cable structure via tape-winding, which is a slow and time-consuming process. By comparison, extrusion trialling has found that h-TPEs are highly compatible with common cable production methods, and can bear very high extrusion speeds while retaining excellent homogenity and finish. This has been found to be the case even when extruding very thin (<1 mm) sections of h-TPE, and complete water blocking has been found at high pressures in samples as thin as 0.7 mm.

As a result, we conclude that this material is potentially highly disruptive for water blocking tape systems, as it delivers superior water blocking capabilities under all conditions, while being easier to handle and deploy within a cable. Currently, cable trials are underway to further optimise the material and develop further functionality, examples of which are laid out below.

2.1. Functionalised h-TPEs with molecular self-healing capabilities

As mentioned previously, smart materials can accomplish ‘asset self-repair’, but not true molecular self-healing. In the above case, h-TPE will deswell if water is removed, which will in turn reveal the original defect. Although investigations have shown that h-TPEs remain responsive through multiple swell-deswell cycles, a more elegant solution would be to develop a hybrid material that combined water swelling and molecular self-healing. In this instance the swelling action to close a defect also promotes a molecular self-healing process to effect a persistent repair.

Gnosys developments based on functional TPEs have targeted the preparation of graft copolymers, where the side-chains are equipped with functionality capable of reversible bonding. The reversible bonding network is designed to be sensitive to stimuli (thermal, damage) and act to form bonds across a defect to restore barrier properties. Prototype self-healing TPEs have been prepared (see Figure 6) that may be deployed alone or in water-swelling formulations.

The reactivity of functional TPEs can also be exploited for the introduction of structural units with specific modes of action. Of note are Gnosys developments complementary to h-TPE applications: the installation of hydroactive fluorophores that will indicate the presence and distribution of water within an h-TPE; and the grafting of TPEs with side-chains promoting enhanced interfacial adhesion in wet environments.

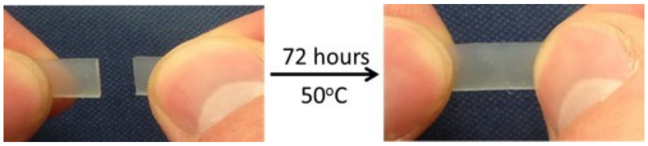

Figure 6. Functionalised h-TPE demonstrating self-healing properties. The sample was bisected, rejoined, and then held at 50°C for 72 hours.

3. ADVANCED INSULATION OILS FOR SELF-REPAIR FLUID FILLED CABLES (FFCS)

While the majority of underground cables are now insulated with a solid polymeric layer, there still remains a sizeable legacy network of FFCs that are either functioning well or are not currently easy to replace. Instead of polymeric insulation, these cables are insulated by layers of tightly lapped paper, impregnated with a low-viscosity mineral oil with good dielectric properties that serves as a heat sink and prevents the formation of voids that can lead to partial discharge events. This is vital, as both overheating and partial discharge phenomena can damage the insulating paper and cause premature aging over the operational time period. This in turn reduces the breakdown voltage of the cable in operation and risks premature asset failure.

In FFCs, the greatest concern is the loss of oil. As the oil in a circuit is held under a positive pressure, any breach in the outer sheath will cause the oil to leak from the insulation layer into the surrounding environment. This will cause the oil pressure to drop, resulting in the eventual formation of voids and the potential malfunction and/or failure of the insulation. If this situation is allowed to continue unchecked, that will result in cable oil levels falling to the critical point where the insulation eventually fails (with consequential cable failure). The leaked oil also has environmental considerations, and operators of FFCs can face heavy fines and expensive unplanned maintenance if a leak is detected in a sensitive region.

As network operators have ceased deploying fluid filled cables in favour of solid polymeric circuits, designing oil-filled cables with self-healing sheaths is not practical. As an alternative, we have examined improvements that can be made through changes within the insulating fluid. Investigations in blending insulation oils with drying oils have shown that the drying oil can cross-link in the presence of atmospheric oxygen thereby forming a preventive seal that would prevent the further leak of insulation oil.

As part of our investigations, we have developed and characterised blends containing currently-used insulation oils and different drying oils, with particular regard given to their reactive, rheological, and electrical properties. An example of a successful system is shown below in Figure 7. In this situation, the oil is challenged by being drained through a block containing a defect of a known size. Upon exposure to oxygen, the oil cures and forms a solid film; this can either immediately block the defect or (as seen in Figure 6) build up a large, solidified mass that prevents further oil flow. In both cases, the cured material prevents the loss of oil into the surrounding environment.

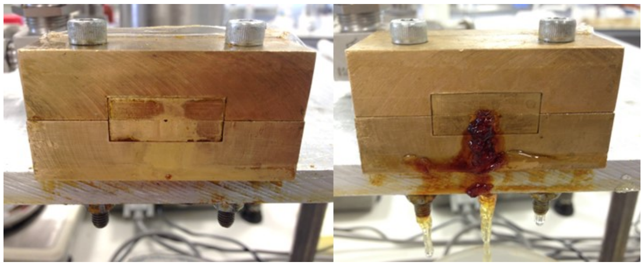

Figure 7. Example defect block (lab-scale mimic of FFC leak scenario) before (left) and after (right) test of the cable repair oil system.

Gnosys has also developed proprietary reactive systems that can be blended with, or entirely existing cable fluids. These oils are intended to provide the same insulative effect as T3788 while also being able to crosslink, substantially simplifing the deployment of self-healing cable oils (Figure 8).

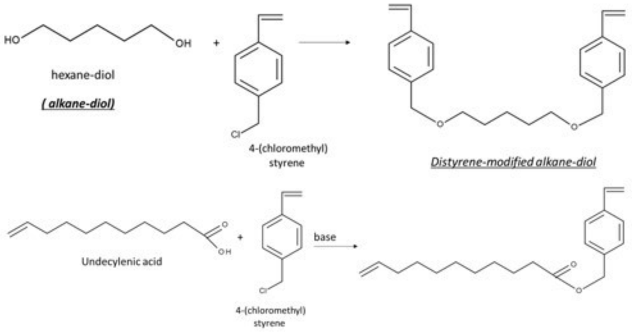

Figure 8. Alternative unsaturated cable-fluid systems.

The starting materials for the synthesis of both the unsaturated alternative systems are commodity items, available in bulk quantities at low prices. Moreover, these systems can be synthesised rapidly and do not generate toxic byproducts. Both the synthetic procedures have been optimised at Gnosys within the scope of this research work and have been proven as efficient with respect to product yield and recovery. Initial characterisation of the resulting products have shown that they possess similar fluid and electrical properties to existing cable fluids woth some enhancement of breakdown strength - further trialling is now underway.

3. References

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