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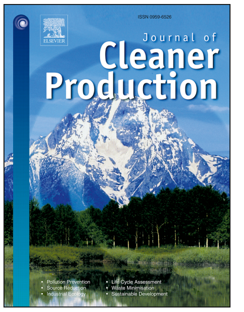

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Self-healing materials: a pathway to immortal products or a risk to circular economy systems?

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1. Introduction

Within a Circular Economy (CE), lifetime extension is a key strategy for preserving and maximising the value of products and components within the system (Tecchio et al., 2017; Montalvo, Peck & Rietveld, 2016). Defined as 'the postponement or reversal of the obsolescence of a product through deliberate intervention' (Bakker & Schuit, 2017, p.12), product lifetime extension can be achieved through tactics such as reuse, maintenance, repair and remanufacturing (Bocken et al., 2016; Nußhol, 2017).

To enable this transition to longer product lifetimes significant research has been conducted within areas of business model innovation (Moreno et al., 2016; Bocken et al., 2016; Whalen, 2019) and design strategies (Bakker et al., 2014; Den Hollander, Bakker, & Hultink, 2017; Bocken et al., 2016). Yet, little attention is given to material innovation and how this may improve the lifespan of the product. Considering the significant impacts that global material resource extraction places on environmental domains, lifetime extension of materials is a critical strategy for mitigating these issues (Olivetti & Cullen, 2018).

Inspired by biological systems, a classification of smart material has emerged with the ability to self-heal or self-repair, allowing for the partial or full restoration of functionality in response to damage (Diesendruck et al., 2015; Bekas et al., 2016). Able to mend both structural and aesthetic deterioration, these materials repair either autonomously through inherent capabilities or as a result of an external trigger such as heat, light or pressure (Ghosh, 2009; Aissa, et al., 2012). Considering that practically all materials and components are vulnerable to both natural and artificial degradation over time, self-healing technology has the potential to significantly improve the reliability and lifetime of products (Ghosh, 2009). Moreover, a key principle of a Circular Economy is to maximise the value of materials, components and products by keeping them cycling for longer (Ellen MacArthur Foundation, 2013), therefore, a technology that can help maintain integrity, such as self-healing could assist in this endeavour. However, thus far, self-healing has predominantly been studied from a material technical perspective, and little consideration has been given to the Circular Economy or sustainability implications of this innovation. Furthermore, many novel materials are rapidly being brought to market by manufacturers, (Roberts, 2015), and their development is being seen as *'a radical shift in society's use of chemistry, the implications of which are only starting to be investigated by environmental scientists'(Roberts & Hill, 2015, p.6).* So, while it is important to explore the contributions that new and smart materials might offer to sustainable product lifetimes and the potential for how these material might be employed, it is vital their risks and limitations be understood as well, providing useful insight to material scientists on their sustainability factors. Therefore, this paper investigates the benefits and challenges that self-healing materials offer to product life extension within the context of the Circular Economy. This next section outlines the background literature associated with both key topics: Circular Economy and Self-healing materials, concluding with the key research question that were examined.

2. Background Literature

A literature review of Self-healing Materials and the Circular Economy was conducted to locate and analyse the opportunities for where these two perspectives might converge. For Self-Healing, it was important to understand the current capability of the technology, the uses, and benefits identified by previous researchers. For the Circular Economy, it was necessary to identify the key factors and principles that relate to product lifetime extension.

The review was conducted using the key words ‘Self-healing’, ‘Self-repair’, ‘Materials’, ‘Lifetime extension’, ‘Repair’, ‘Definitions’, ‘Circular Economy’ and ‘Sustainability’ utilising Scopus and Google Scholar. Journal articles and grey literature were reviewed and the data used to identify the state of art of both fields. Several searches were conducted using different combinations of the keywords supplied and no time frame was applied. Considering the field of self-healing materials is located primarily within chemistry and bio-chemistry sciences, review papers were favoured as they provided the most accessible data for those not from this discipline. As result of these searches, 368 papers and conference proceedings were found. The titles, then abstracts were analysed to determine their relevance, and if deemed appropriate the whole paper processed. After this filtering process took place, 46 papers were identified as relevant and reviewed. The results from this can be found in the next section.

2.1 Circular Economy

The Circular Economy developed from philosophies such as cradle-to-cradle thinking, industrial ecology, the performance economy and regenerative design (Merli, Presiosi & Acampora, 2017; Lewandowski, 2016). Although a concept that is still emerging and developing (Kirchherr, Reike & Hekkert, 2017), the Circular Economy is broadly understood a regenerative system that aims to minimise resource input, waste and energy leakage by slowing and closing of material and energy loops (Geissdoerfer et al., 2016).

A multi-level approach to sustainable development**,** the Circular Economy challenges the notion that materials and products have an end-of-life (Kirchherr, Reike & Hekkert, 2017; Lewandowski, 2016). It is proposed that through the application of novel circular business models (Whalen, 2019; Tukker, 2015), the use of renewable energy and renewable resources (Lewandowski, 2016), and practices that involve reducing, reusing, recycling and recovering materials and components (Kirchherr, Reike & Hekkert, 2017) positive value can be delivered to the environment, society and the economy.

When considering the perspective of preserving and maximising value within the system, the strategy to ‘keep products, components and materials cycling for longer’ is the most relevant (Ellen MacArthur Foundation, 2013). At a product level this is delivered through lifetime extension.

To facilitate longer product lifetimes, previous researchers have argued that this needs to be addressed from both a business model and design strategy perspective (Bocken et al., 2016). For business models, new archetypes have been proposed (Moreno et al., 2016; Bocken et al., 2016; Bakker et al., 2014; Whalen, 2019) and the challenges and barriers of adoption discussed (Linder & Williander, 2015; Oghazi & Mostaghel, 2018). For design strategies, various ‘design for x’ tactics have been suggested (Bakker et al., 2014; Moreno et al., 2016; Den Hollander, Bakker, & Hultink, 2017; Bocken et al., 2016). Furthermore, organisations should not only be embracing access and performance based models (Bakker et al., 2014) but also considering strategies such as design for physical and emotional durability, repair, maintenance, upgrading, refurbishment and remanufacture (Den Hollander, Bakker, & Hultink, 2017).

Of these strategies, repair and maintenance has been proposed as a particularly vital strategy for Circular and Sustainability systems, as it allows for a greater material efficiency (Stahel, 2013). According to the Principle of Inertia proposed by Stahel (2010), repairing practices address or replace the smallest part of the technical system, therefore allowing the highest economic value to be preserved. As a result, the concept of ‘design for repair’ or ‘repairability’ has been proposed and explored by many previous researchers as a means of extending the lifetime of products in order to reduce their environmental burden (Van Nes & Cramer, 2005; Bakker et al., 2014; Bakker & Schuit, 2017; Prakash et al., 2016; Ackermann, 2018).

From a materials and design perspective, some researchers have explored the development of tools and frameworks that enable more 'sustainable' material choices, such as the SPICE model (Prendeville, Connor & Palmer, 2014), MATto (Allione et al., 2012), framework for material change (Bridgens & Lilley, 2017). But, these are primarily for established materials do not include considerations such as repairability.

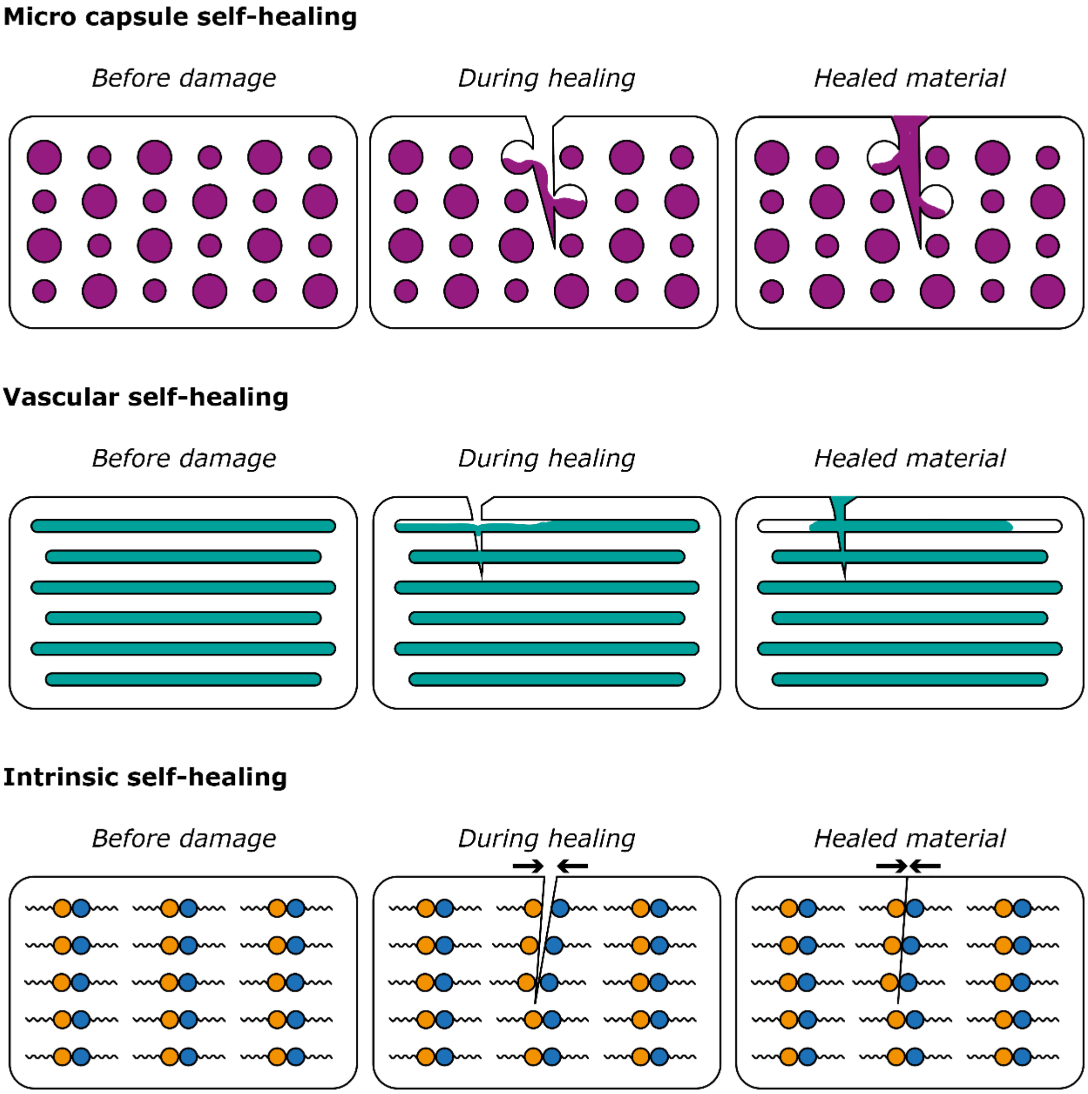
In summary, repair and repairability has shown to be a central strategy for product lifetime extension within sustainability and circular economy approaches. However, most studies are primarily focused on the repair and maintenance at a product and component level, and little consideration given to the repairability of the materials used. Therefore, there lies an opportunity for this field of study to explore how this strategy might operate as a material level.

2.2 Self-healing Materials

Classifications of self-healing materials

Self-healing materials are described as being either, intrinsic or extrinsic. Intrinsic self-healing involves the reforming of chemical bonds at a molecular level, and is triggered by stimuli such as heat, electrical or mechanical force (Hager, 2010; Blaiszik et al., 2010). An example of this is self-healing Poly-urethane. It is material that can be cut and the edges pressed back together and re-bonded to restore functionality (Du et al., 2013). Whereas, extrinsic self-healing introduces a sequestered healing fluid, such as synthetic resins or a biological equivalent to the damaged site either through microcapsules or vascular networks embedded into the bulk of the material (Guadagno et al., 2014; Blaiszik et al., 2010; Coillot et al., 2010; De Muynck et al., 2008). An example of this is self-healing concrete, whereby bacteria is able to produce calcium carbonate to repair the crack. Figure 1 below demonstrates how these mechanism work in more detail.

Figure 1. Extrinsic and intrinsic self-healing mechanisms



In addition to being described as intrinsic or extrinsic, when considering self-healing at a product level, the context and external factors need to be considered as well, thus requiring more detailed classifications. Cseke et al., 2020, propose that the manner in which healing occurs within products can also be expressed as a maturity index from 'Enhanced Durability' through to 'Fully Autonomous' (Table 1)

Table. 1 Self-healing Maturity Index (Cseke et al., 2020)

Enhanced Durability	Assisted Healing	Semi-autonomous	Fully Autonomous
Healing occurs at a molecular level increasing the durability, lifespan and reliability of materials	Healing is triggered by intentional or deliberate external stimuli (heat, radiation, pressure, electricity)	Healing is activated by the operational environment, not the damage itself	Healing is triggered by the damage itself requiring no intentional external intervention

Types of self-healing materials

Developed as both coatings and bulk materials, self-healing has been explored within a range of material systems, such as concrete (De Muynck et al., 2008; Sarker et al., 2015), asphalt (Pamulapati et al., 2017; Xu et al., 2018), glass (Coillot et al., 2010; Singh, 2014), ceramics (Tao et al., 2017) and polymers (Gordon et al., 2017; Hia, Vahedi & Pasbakhsh, 2016; Mauldin & Kessler, 2010). Within each material group, different mechanisms of self-healing have been explored, with the most variations developed within polymers. Table 2 below summarises examples of these materials and how the self-healing triggered.

Table 2. Self-healing material examples

Material	Mechanism	Example uses	Type	Maturity index
Concrete	Encapsulated bacteria producing calcium carbonate (Sarker et al., 2015)	Buildings, bridges	Extrinsic	Fully Autonomous
Asphalt	Microcapsules containing healing agent (Xu et al., 2018)	Roads, pavements	Extrinsic and Intrinsic	Fully Autonomous / Assisted Healing
	Metallic fibres inserted and healed using inductive heating (Pamulapati et al., 2017)	Roads, pavements	Intrinsic	Assisted Healing
Glasses	Encapsulated Vanadium Bromide oxidises sealing crack 400-700C (Coillot et al., 2010)	Fuel cells	Extrinsic	Assisted Healing
	Seals for solid oxide fuel cells (SOFC) operating conditions trigger healing (Singh, 2014)	Fuel cells	Extrinsic	Semi-autonomous
Polymers and polymer composites	Capsule based healing using Epoxy Resin (Guadagno et al., 2014)	Structural composites	Extrinsic	Fully Autonomous
	Resin filled fibre glass vascular networks within carbon reinforced polymers (Williams, Bond & Trask, 2009)	Aerospace wings, wind turbine blades	Extrinsic	Fully Autonomous
	Recyclable thermally healed thermoset Polyketone (Zhang, Broekhuis & Picchioni, 2009)	Printed circuit board, electronic insulation	Intrinsic	Assisted healing
	Thermoplastics such as Poly-urethane (Du et al., 2013)	Flooring, seals, footwear, straps	Intrinsic	Assisted healing
	Self-healing Polyurethane coatings (Nei Corporation, 2020)	Consumer electronics, automotive	Intrinsic	Assisted healing
	Graphene nanosheets embedded into intrinsic self-healing polyurethane (Lin *et al.*, 2018)	Conductive flexible electronic devices	Intrinsic	Fully Autonomous
Metals	Microencapsulated eutectic gallium–indium (Ga–In) embedded into Gold (Au) multi-layered circuits (Blaiszik *et al.*, 2012)	Self-healing circuits for microelectronics	Extrinsic	Fully Autonomous

A topic of interest within the fields of chemistry, bio-chemistry and material science for the last two decades, over this time different materials groups have been advanced to varying levels of technological development. Though some self-healing polymer coatings are commercially available (Nei Corporation, 2020; Autonomic materials, 2020), most self-healing glasses and ceramics have primarily been investigated within lab-based environments (Coillot et al., 2010; Tao et al., 2017).

While others, such as self-healing concrete and asphalt are currently being field testing within bridges and roads (Davies et al., 2018; Xu et al., 2018).

Applications

Despite their advanced properties only a few self-healing technologies have been applied at a product level. Self-healing car tires (Continental, n.d), bicycle tires (Slime Products, 2019), self-healing gas tanks (HIT-USA, 2019), and self-healing jackets and bags (Imperial Motion, n.d.) are examples of commercially available products. Still, considering the enhanced functionality these materials might provide, previous researchers have proposed many more sectors that could also benefit from this innovation. Table 3 below outline these.

Table 3. Summary of sectors that could benefit from self-healing materials

Sectors	**Uses**
Aerospace	Withstand harsh operating conditions such as jet engines (Das, 2016) or deep space (Gordon et al., 2017); polymeric materials for space vehicles, vehicle and aircraft fuel tanks and composites versions for inflatable space applications (Grande et al., 2013)
Batteries and fuel cells	Glass for seals in solid oxide fuel cells (Singh, 2014); Glassy material for high temp enamel reactors (Coillot et al., 2010)
Consumer electronics	Self-healing liquid metal–elastomer composite for robust soft-matter robotics (Markvicka et al., 2018); Conductive hydrogel for flexible electrode, sensors, and wearable devices (Rong et al., 2017)
Medical industry	Prosthetic limbs (Hia, Vahedi & Pasbakhsh 2016) and synthetic skin (Wu et al., 2017). Recyclable, silicone elastomer for artificial muscles, medical implants (Ogliani et al., 2018); Conductive, stretchable, sticky hydrogel for tissue adhesives, implantable electronic devices, tissue repair, medical adhesives (Wang et al., 2018)
Construction	Concrete structures, i.e. buildings, bridges (Sarkar et al., 2015; Davies et al., 2018)
Transport	Non-asbestos composite brake pads (Zhang, Dong & Zhang, 2009); Non-swelling polymer for marine applications, fishing and shipping industry, offshore facilities (Kim, Hyun and Han, 2018)

In summary, the review of self-healing revealed that most research within this space is from a material science, chemistry and bio-chemistry perspective, proposing new compositions of self-healing materials and mechanisms. Explorations within the field of engineering are primarily aerospace and construction focused and few examine this from a design perspective. Though potential applications are suggested and their likely benefits discussed, little consideration is given to the sustainability or Circular Economy implications of this smart material. Moreover, most studies are primarily conducted in academic environments and have not considered an industrial perspective.

In conclusion, this review has outlined the limitations from both fields of study for how these two perspective converge. It highlights that while repairability is a central strategy for circular and sustainable products, this is not addressed at a material level. Whereas for self-healing studies, though new materials are being proposed their sustainability potential, industrial opportunities or risks are rarely discussed. Considering that the enhanced functionality of this material has not only the capacity to assist in product and component lifetime extension, but also expand our understanding of how smart materials might be used within the design and engineering of sustainable products, further investigation is required. Therefore, this study examined this key research question:

'What are the benefits, opportunities, limitations and risks that are associated with implementing self-healing materials within sustainability and circular economy contexts?'

To examine this question, in addition to analysing the literature, this study also gathered data from industry experts to better inform how and where these materials might operate in practice. The next section outlines the methods used in more detail.

3. Methodology

To address the research question defined and validate assumptions drawn from the literature review, an empirical study was carried out in two phases.

The purpose of phase one was to consolidate insights from the literature and examine these in respect to the industrial perspective. A scoping survey was undertaken with 14 industrial representatives from design, manufacturing backgrounds providing a broad understanding of the benefits, opportunities for applying self-healing materials to products. The purpose of phase two was to further interrogate and validate findings from phase one and expand upon the sustainability and circular economy considerations of implementing self-healing materials. A combination of round table discussions, a workshop and expert interviews were selected to enable the most effective and convenient engagement with the industrial representatives. This was undertaken with a further 18 industrial representatives operating across the value chain, including those working in materials fabrication, product design and manufacture, waste management and refurbishment. The workshop and round table sessions allowed for richer feedback of insights and more in-depth discussion. Interviews were employed at the end of research to ensure that particular perspectives that had not yet been captured from experts across the value chain were considered. Table 4 and provides a summary of the activities and the participants involved.

Table 4. Overview of methods used within the study

<table>
<tr><th></th><th>Activity</th><th>Participants</th><th>Purpose</th></tr>
<tr><td rowspan="3">Phase 1</td><td>Literature Review</td><td></td><td>Uncover the state of art of self-healing technologies and product lifetime extension strategies</td></tr>
<tr><td>Scoping Survey</td><td>14 experts from design, manufacturing</td><td>Understand the issues manufacturers face around damage and how self-healing might apply to their products</td></tr>
<tr><td>Analysis and consolidation</td><td></td><td>Consolidate insights from literature and scoping survey and use these to inform questions asked in the round table discussions, workshop and interviews</td></tr>
<tr><td rowspan="5">Phase 2</td><td>Roundtable discussion 1</td><td>4 experts from design, sustainability, manufacturing</td><td rowspan="4">Gain insight from industry for how this technology might be used in their sectors and the challenges for implementation and sustainability.</td></tr>
<tr><td>Round table discussion 2</td><td>3 experts from repair, refurbishing</td></tr>
<tr><td>Workshop</td><td>8 experts from manufacturing, chemical industry, consulting, government, design</td></tr>
<tr><td>Semi-structured Interviews</td><td>3 experts from materials research, waste management, circular economy</td></tr>
<tr><td>Thematic Analysis</td><td></td><td>Analyse all outputs from research activities in order to identify the key themes and concepts</td></tr>
</table>

Phase one

The survey was conducted using Qualtrics and was distributed amongst those involved in the design and development of products. 14 responses were recorded, and the data was used to understand what challenges manufactures face regarding damage and how self-healing material might be used within their respective sectors. Participants were from the following industries: healthcare and consumer electronics, defence, aerospace, energy, FMCG, high value manufacturing, design. In addition to questions, information was provided to participants informing them what materials currently self-heal and how this is achieved. This was employed to allow for more cognisant responses from the participants for how this technology might be used in their products or processes.

The data from the survey was analysed using content analysis (Stemler, 2000) in order to categorise the textual data and consolidate it along with the insights from the literature review. Findings were used not only to help inform the development of the topics and questions within the roundtable discussions, workshops and interviews but also were analysed along with subsequent data collected.

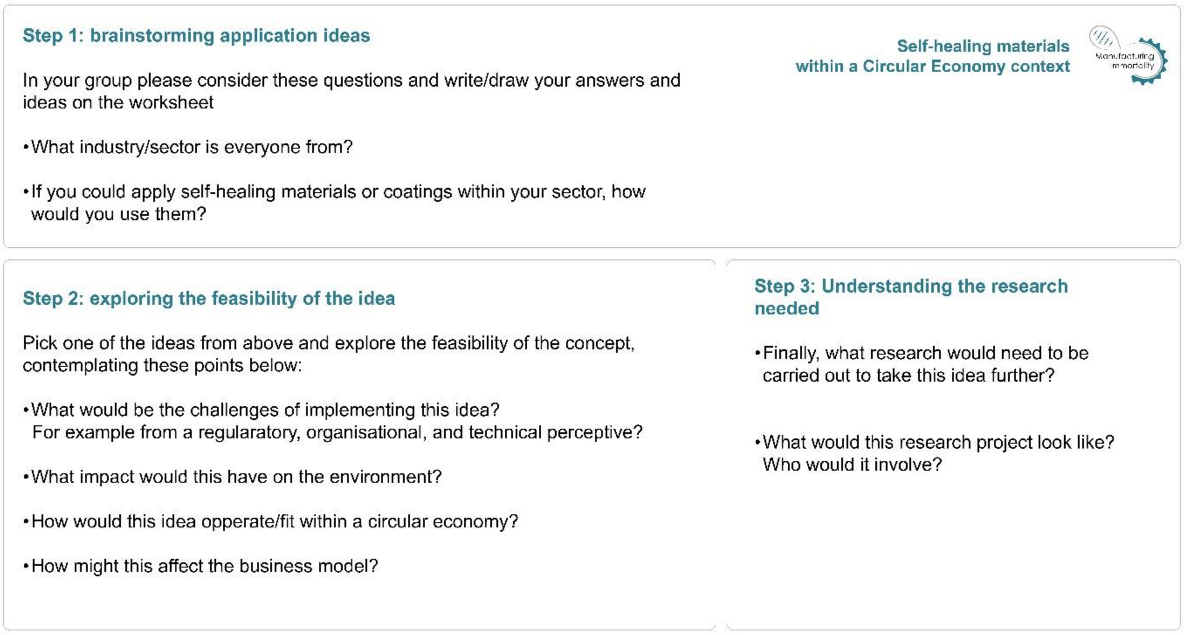
Phase two

Roundtable discussion 1: was conducted at an industry focused CE event with 4 experts from design and manufacturing (P1 - sustainability manager at a global electronics repairer, P2 - head of strategy at packaging manufacturer, P3 – environmental manager at healthcare and electronics manufacturer, P4 - environmental programme manager at consumer electronics manufacturer). A slideshow introducing self-healing materials was presented, which included initial findings and insights uncovered from phase one. This was followed by a facilitated discussion, whereby experts were asked to share their responses regarding how these materials might be applied and what sustainability or circular economy issues might arise if they were implemented.

Roundtable discussion 2: was conducted at the factory of a consumer electronics repair and refurbisher and was attended by 3 experts from the same company. (P1 – sustainability manager, P2 – marketing manager, P3 – program director). Following a tour of their facilities and operations, a presentation was given introducing self-healing materials, as well as initial findings and insight from phase one. A facilitated discussion then took place whereby the experts were asked to share their response on how this technology might benefit lifespan and repair of consumer electronics.

The workshop: was carried out at an industry focused CE event with 8 experts from manufacturing, material fabrication, local government and consulting. (P1 – environmental manager at electronics refurbisher, P2 – Founder of fashion and textiles manufacturer, P3 – consultant, P4 – program manager in local government, P5 – researcher at chemical and materials manufacturing, P6 – product manager at engineering services, P7 – CE analyst at environmental NGO, P8 – sustainability director at design consultancy). This session involved a presentation, hands-on experimentation with self-healing materials and concluded with a workshop style activity whereby participants filled in worksheets in two groups. See figure 2 below.

Figure 2. Worksheet from Self-healing materials workshop

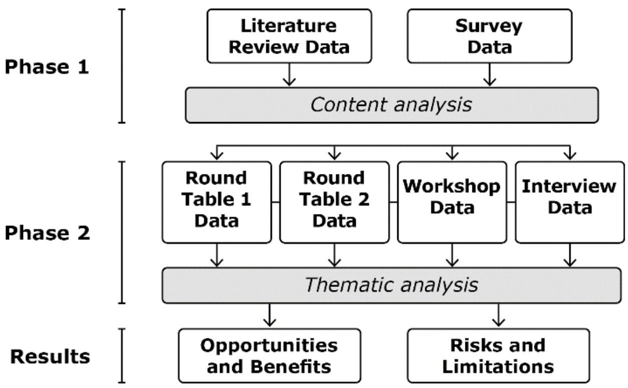


The exercise consisted of three steps: 1 – the brainstorming of application ideas within their own sector; 2 – exploring feasibility of the concepts in more detail contemplating environmental, regulatory and finical implications; 3 – identification of future research directions. A group discussion took place at the close of the session and any additional insights were captured.

The semi-structured interviews were conducted with three experts working in the fields of waste management, self-healing materials and Circular Economy. Participants were given an overview of self-healing materials and then asked to share their response on the benefits and challenges for implementing these within circular industrial systems.

To analyse the data collected thematic analysis was employed. Thematic analysis is 'a method for systematically identifying, organizing, and offering insight into patterns of meaning (themes) across a data set' (Braun & Clarke, 2012, p.57). This framework allowed the research to ascertain which factors were the most prevalent and salient in regard to the research question defined. All insights were then assessed in relation to CE factors outlined in the review, such as maintenance, repair, refurbish and remanufacture and thematically grouped to demonstrate the benefits, opportunities, risks and limitations of implementing self-healing materials within a Circular Economy context. Figure 3 demonstrates this process in full and results are shown in the next section.

Figure 3. Process of research methods used



4 - Results and Discussion

The key themes that emerged from the data are divided into two main themes and several sub themes (see below). These represent the structure of this next section and are expanded upon using literature examples and data from participants.

4.1 Opportunities and Benefits

4.1.1 Maintaining the primary lifetime of the product

- Technical Lifetime
- Service Lifetime

4.1.2 Refurbish and remanufacture

- Increase the ease of disassembly and reassembly

4.1.3 Enable alternative business models

4.2 Risks and Limitations

4.2.1 Persistence

4.2.1 Technosphere or biosphere? – hybridization of materials

4.2.3 Cycling of these materials – new waste streams, value of recovery

4.2.4 Development, performance and environmental trade-offs

4.2.5 Compliance and liability

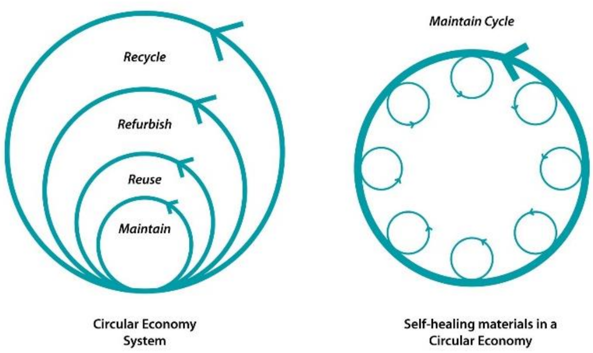
4.1 Opportunities and benefits for Self-healing

4.1.1 Maintain the primary lifetime of the product

One of the principal benefits of a self-healing technology is that it can potentially extend the primary lifetime of a product or component. This has been observed in the literature by several authors (Wool, 2008; Aissa, et al., 2012; Hager et al., 2010; Diesendruck et al., 2015), and also highlighted within the roundtable, workshops and interviews. It was remarked, that a product that is able to self-healing, could '*help to preserve an object's integrity, complexity and embedded energy'*. Consequently, as this would increases the lifespan it could also potentially reduce the demand for natural resources and increase the utilization of existing stocks (Olivetti & Cullen, 2018).

Moreover, considering that some materials are able to heal in situ, with no or minimal human intervention, from the perspective of the Inertia principle, the smallest part of the system is being addressed and most economic and material value preserved (Stahel, 2010). A notion previously identified by Akrivos et al., (2019), they suggested that self-healing systems are associated with the inner loop of the technical cycle, providing a loop of 'Maintenance' thereby extending the products lifespan (figure 4).

Figure 4. Framework for self-healing in a Circular Economy (Akrivos et al., 2019)



However, if the lifespan of the product is considered in more detail, according to Cooper (2010), it can be viewed from two perspectives, the technical life and service life.

The *technical lifespan* refers to the maximum period of time a product has the ability to physically function, the *service lifespan* as total period of time a product is in use before is disposed of (Cooper, 2010). Although an important distinction for demonstrating how functioning products are often disposed of prematurely, for self-healing it provides a lens for analysing how this functionality might be understood and applied to products.

So, if considered through this perspective, self-healing can assist firstly, with the technical lifetime of the product, by maintaining its functional and structural properties, preventing issues participants offered such as: '*Bulk material failure due to overload' or 'Fatigue, impact, and environmental degradation'.* And secondly the service lifetime of the product, by preserving its aesthetic functionality, which could help to mitigate issues of wear and tear. As participants suggested that *'minor defect like cracks on glass' or* '*scratches dues to mechanical damage'* often result in premature disposal.

Technical life perspective

A key output of these self-healing systems is the ability to slow down the ageing and degradation of materials and products (Aissa et al., 2012; Ghosh, 2009; Schlangen & Sangadji, 2013). A useful function for any system, several opportunities within the construction, electronics, energy, medical sectors were offered by participants and within the literature where self-healing would be particularly salient.

Firstly, self-healing could be highly beneficial within scenarios where damage is not easily detected, such as in construction or complex electronic products. Within construction, as a result of environmental stress, materials such as concrete or asphalt can develop micro cracks within the bulk of the material which affects the overall integrity increasing the likelihood that critical failure will occur (Herbert & Li, 2013; Su et al., 2017). Furthermore, when materials are deployed in products that operate in extreme environments, the cost and risk associated with such a repair can also be high (Hager et al., 2012; Aissa et al., 2010). Thus, it was suggested both within the literature and by several participants that self-healing could be useful for products that are '*large and have a long lifetime'* such as pipes, bridges, marine based structures or deep sea cabling and connectors. For electronics, if failures occur inside a complex product this can be both hard to detect and access, thus researchers are developing both self-healing circuits (Markvicka et al., 2018; Blaiszik *et al.*, 2012) and self-healing wire insulation (Nasa, n.d) to mitigate some of these issues.

Self-healing could also be used to maintain the efficiency of energy producing products. Wind turbines blades are subject to extreme external stresses when in operation, affecting their efficiency (Yang, 2013). Likewise, due to solar irradiation, solar panels can discolour over time, decreasing their efficiency and overall lifespan (Kaplani, 2012). However, self-healing systems could be integrated as part of the composites within wind turbine blades (Fifo, Ryan & Basu, 2015) or self-healing glasses deployed within the top layer of solar panel to prevent radiation damage (Heng et al.,2015). This would not only help to enhance the durability of these products, maintain efficiency, increase reliability, but also reduce cost and risk associated with repair.

Secondly, another relevant scenario for this technology is within medical products and wearable electronic devices. Implants such as pacemakers or prosthetic joints can be both very costly and pose great risk to human life if they need removing or repairing (Costea et al., 2008). Thus, materials that had enhanced durability and could repair at a molecular level as stresses occurs, would be highly beneficial (Hai, Vahedi & Pasbakhsh, 2016). A point that one participant working within orthopaedics highlighted as important also, stating that '*Self-cleaning and self-repairing materials that strengthen with stress would be amazing'*.

Electronic wearables is a growth industry expected to reach €77 Billion by 2022 (Delliotte, 2019). Currently, these types of devices are made from materials that are rigid and brittle, which increases the likelihood of damage through use (Markvicka, et al., 2018). However the application of self-healing soft electronics to wearable devices, would not only increase durability, reduce the amount of materials needed, but also provide functionality not currently possible with traditional materials (Kang, Tok & Ba, 2019).

Lastly, it was also observed that these materials are not only significant for products that have high value and long life spans (Fifo, Ryan & Basu, 2015), but also products and components that either have multi-material joints, or are subject to high levels of wear and tear. Several participants suggested self-healing would be useful in scenarios where failure occurs because of '*Interfaces between dis-similar materials'* or because of *'Differential thermal expansion'* an issue that could potentially be mitigated through self-healing adhesives.

For products and components are subject to high levels of wear and tear, these can be items such as electronic cables, shoes, brake pads, tires and wheels. An issue some manufactures are attempting to address (Continental, N.d.). However it was observed that this would be particularly relevant for products deployed within public infrastructure. One participant working within the public sector offered that '*roads, public furniture, lighting, and transport'* could also benefit from self-healing coatings as in addition to lifetime extension they would also help to maintain the quality and aesthetic perception social spaces.

Service lifetime perspective

Beyond repairing functional and structural damage of products, self-healing materials also have the opportunity to mitigate issues relating to emotional obsolescence, whereby products are discarded due to cosmetic damage. Wear and tear is a key factor for why functioning durable products are prematurely replaced by consumers (Van Nes & Cramer, 2005), thus the aesthetic durability of products must be anticipated as part of the lifetime extension strategies as well (Bakker et al., 2014). From our data, this was observed to be relevant across multiple stages of the product's lifetime.

Prior to use, several participants remarked that during manufacture, transport or installation damages such as scratches or cracks to products can occur, resulting in wastage. With products such as built-in home appliances, this not affects the user's perception of the product but also incurs costs for replacement. But, if self-healing glasses or coatings were to be integrated to particular components or surfaces '*this could definitely do the job of lowering waste* rates'.

Within the use phase, the application of self-healing paints or coatings to alleviate wear and tear is primarily discussed within the automotive sector (AutoScene, 2009; Nissan Motor Corporation, n.d). Similarly one participant from the transportation industry offered that this could be especially advantageous for smaller transport products that are rented or leased, especially the '*bicycle frames and scooters grips'*, as these components have high levels of wear and tear and frequently need to be repaired and replaced.

Within the survey, several consumer appliance manufactures and designers remarked that self-healing surfaces would also be highly beneficial for fridges, ovens and cookers as well, as their *'consumers are looking for durable surfaces that look premium and are easy to clean'*.

Overall, while each of these examples could benefit from this technology, arguably there are also 'shorter living products' such as laptops, phones and home appliances, which could might benefit as well, as aesthetic degradation of these products tends to significantly affect their lifespan.

Cracked screens are one of the most common issues for mobile users across the globe (Mintel, 2018). While some researchers are looking at increasing the strength of the glass (Gao et al., 2019), other are considering self-healing glasses (Kim et al., 2020), and self-healing phone screens are now being patented by organisations such as Motorola (Wood & Green, 2017).

Another example of this is in regard to TV and broadband boxes. These products can have a lifespan of up 8 years and be installed in up to 5 different households across their lifetime (Boddington & Hubert, 2016). Although the internal electronics are tested and reused, the outer casings, if scratched or damaged are often replaced. One participant within the study is involved in the repair and refurbishment of these products, and commented that this scenario places a significant environmental and economic cost to both the manufacturer and the refurbisher of these products. However, if a self-healing coating were to be applied to these products it could elevate this issue, as it would allow these products to be returned to a like new condition between different users. It was also remarked that for this scenario, from a business perspective, triggered self-healing would be preferred over autonomous self-healing. This would assist the refurbisher in being aware of what damage has occurred during use and allow them provide the service of repair to their customers.

Lastly, it was offered by a group participants that if the servitisation of products such as washing machines, fridges or furniture were to become more common place, organisations might be looking for methods for maintaining the aesthetic resilience of their products, thus 'a *self-healing surface that keeps products looking good for longer'* would be of great interest.

4.1.2 Refurbish and remanufacture

Increase the ease of disassembly and reassembly

A key challenge of product life extension, is the ease at which products can be disassembled and accessed when needing to be repaired, inspected or maintained. For many products, disassembly often damages components more significantly, decreasing the likelihood that they will be reused or valuable materials recovered (Vanegas et al., 2018; IFixit, 2020).

Considering that some self-healing rubbers can repair up to 18 hours after they have been cut (Cordier et al., 2008), this type of extended material functionality could, for example, contribute to the ease at which products are able to be dis-assembled and reassembled within refurbish and remanufacture practices. Instead of product designed with clunky fixings to be taken apart if needing repair. Products could be designed to be entirely sealed casings able to be cut open and then resealed. Thereby potentially reducing the number of components and materials that would be needed to make a product.

This functional benefit could be useful for a variety of different products, especially those within consumer electronics. One the most frequently replaced components of a mobile or tablet is a damaged screen (Benton, Coats & Hazell, 2015). However, as indicated by the participant who refurbishes consumer electronics, due to methods used in assembly of the screens separating the different layers for repair often results in further damage and value loss. Similarly, within the context of wearable technologies often components containing rare earth metals are designed for seamless, permanent integration, resulting in e-waste issues (Gurova et al., 2020). Thus, self-healing polymers, adhesives or hydrogels that could be easily cut and re-bonded could help alleviate this issue.

This situation is particularly important when considered within the context of the Circular Economy; as, if we are aiming to keep product, components and materials cycling for a long as possible, additional insight and potential strategies that facilitate this would be salient for the field.

4.1.3 Enable alternative business models

Adopting alternative business models is a key strategy for incentivizing organisations to develop durable, long-life, reusable products (Bakker & Schuit, 2017). Whereas, within linear systems, where the majority of economic value is captured from the one-off sales of goods or services, in circular systems, commercial value is reconciled with the adoption of circular strategies such as product lifetime extension, and revenue delivered through service systems such as access-based models (Nuβholz, 2018). Considering that self-healing materials inherently extend the useful service life of product, the typical linear model may not be fit for purpose. Thus, if organizations were to employ self-healing systems into their products, this could incentivize them to consider alternative business models as they would be interested in maintaining the lifespan of an asset in order to extract the maximum value. While integrating self-healing technology may initially be more expensive, additional costs incurred from integrating lifetime extension technologies could be offset from by additional revenue from the product being in use longer (Bocken et al., 2016).

4.2 Risks and limitations for self-healing in circular systems

4.2.1 Persistence

Within polymers, material properties such as high durability are a key functional benefit while in use. But, from environmental perspective, this same characteristic can lead to persistence of synthetic polymers in marine environments causing harm to natural organisms (Andrady, 2015). Similarly within Circular systems, when assessing the toxicological and eco-toxicological characteristics of materials flows within the technoshere and biosphere persistence is also considered (Braungart, McDonough & Bollinger, 2007). Therefore, several participants observed that if materials have the ability to either re-bond or release 'healing agents' autonomously with no deliberate human action, this might present issues at end of life, especially if they fall out of the value chain.

4.2.1 Technosphere or biosphere? – hybridization of materials

A founding principle of the Circular Economy is the separation of Technical nutrients from Biological nutrients (McDonough & Braungart, 2002). This is to ensure that pure waste streams can be developed and materials and components able to easily cycle (Ellen MacArthur Foundation, 2013). For self-healing, the inclusion of biological components such as bacteria into materials like concrete and polymers, raises queries regarding which cycle they should belong to. Thus, it was recommended by participants that future researchers exploring bio-hybrid self-healing materials need to consider strategies that allow these biological components to be easily and safely removed or deactivated. This is to ensure they are not creating a new category of monstrous hybrid materials (McDonough & Braungart, 2002), that cannot be managed at end of life.

4.2.3 Cycling of these materials – new waste streams, value of recovery

Novel or innovative materials such as high performance composites, while they offer some energy and efficiency savings in their primary lifetime, when considered over their entire life cycle can often be problematic as most are unable to be separated or reused and with most likely to end up in landfill

(Roberts, 2015; Hazell, 2017). A participant who is an expert in self-healing materials suggested this would be a similar outcome with some extrinsic self-healing materials, especially those that are composites and integrate resins.

For some intrinsic self-healing materials such as Poly-urethane, they are not too dissimilar to their non-healing counterpart, thus could be recycled. A scenario that could be arranged as one participant who is a waste manager stated, *'The system will evolve to recapture it as long as there is a market for it'.* However, arguably this could present issues as well. Some self-healing materials are similar in materiality (look, behaviour) to their non-self-healing counterpart. This would affect their ability to be sorted and recaptured as the '*look and feel of the material defines how it sorted'*. Hence, these materials could be sorted into established waste streams, potentially causing contamination or loss of value. Moreover, if deployed as a coating rather than bulk material recovering these may not be environmentally or economically beneficial. Nevertheless, as stated large scale waste management organisations are able process new types of materials, as long as the sufficient research has been carried out on how to manage it at end of life.

4.2.4 Technology Development, performance and environmental trade-offs

One limitation of this field of enquiry is that only a few of these materials have been tested and applied outside of the laboratory environment. While several different types of self-healing coatings are available commercially (Nei Corporation, 2020; Autonomic materials, 2020; Wong et al., 2011), the technology diffusion of the self-healing bulk materials has been slower. Whether it is lack of suitable applications, use cases, or that it is just too early within their technological development, further research needs to be carried out to fully assess this situation.

Another limitation is that while self-healing has shown to be effective at repairing small scale damages such as micro cracks and scratches, the healing of larger damages is not yet possible (White et al., 2014). Initial studies have attempted to mitigate this through the introduction of shape memory polymers to close larger damages (Ferguson et al., 2014), while others have proposed gel-like substances that behave as scaffolds for the self-healing to take place (White et al., 2014). However, the true performance of these materials is yet to be known.

4.2.5 Compliance and liability

One factor that most participants highlighted as central barrier for adopting self-healing into their products are issues around liability. All commercially available products must be CE compliant to ensure they meet the appropriate health and safety standards of the EU (gov.net, 2020). So, considering that standards for assessing self-healing materials are still being defined, and are principally used as a method for assessing performance (Bekas et al., 2015), a greater understanding of health and safety and their liability needs to be understood. As it was remarked that organisations will want know what it is the *'safety and liability of keeping a healed product in service'.*

5. Future Research Opportunities

Within the body of this paper, many benefits, opportunities, risks and limitations were identified for self-healing materials within the context of a Circular Economy. Self-healing as a concept shows a great deal of promise, especially as a strategy for product lifetime extension in order to help preserve the embedded value of a product i.e. time, money, energy, resources, etc. However, it is important to note that a great number of questions also remain unanswered regarding their performance, ability to be produced at scale and how they will be managed at end of life. Moreover, the data from this study was only collected from the literature and insights from industrial experts. Self-healing materials are not yet widely used in industrial application, therefore to fully validate the findings additional design and engineering research would need to be carried out. Thus, this study has identified three keys areas of development that would advance the field of self-healing and help to confirm the factors identified.

5.1 Metrics, models and measures of value

One area of improvement for this technology is for the development of appropriate metrics and models for understanding the true environmental, economic and societal value and impact of this technology. The market for self-healing materials is anticipated to grow over the next 10 years within the electronics, automotive and construction sectors (Grand View Research, 2017), yet few studies have been able to quantitatively demonstrate the overall savings that can be made.

While several Life Cycle Assessments have been conducted (Belleghem et al., 2017; Lizasoain-Arteaga, 2019; Vanden Heede, 2019; Vanden Heede, 2018; Chatterjee, 2019; Rigamonti et al., 2019), these are only for concrete and asphalt materials and did not include end of life considerations.

If these materials are to be adopted more comprehensively by industry, not only must the environmental trade-offs of creating a more complex material need to be understood but also the economic factors as well. Therefore, it is recommended that more detailed models and metrics need to be developed that assess both the quantitative perspective but also the qualitative perspective such as the societal and consumer benefits.

5.2 Technology developments and applications

Aside from the commercially available self-healing coatings, many materials uncovered in the literature are at Technology Readiness Level (TRL) 1-3. This means that the majority of self-healing technologies have only been proven within lab based conditions. How these materials will operate and heal in real world scenarios needs to be more comprehensively understood, thus future research focusing on applied testing should be carried out. While it could be argued that self-healing as a technology just requires more time to develop, if more industrial focused explorations are not carried out this field of study will continue to remain lab based research. Thus, the results of this study provide a series of suggestions for what could be investigated and the benefits they might offer, which could help future researchers and industry to secure funding to explore these ideas.

5.3 Cross disciplinary collaboration

One of the key limitations identified with novel materials within Circular Economy systems is that often at end of life these materials cannot be reused or recycled. However, as Hazell (2017, p.2) offers *"This isn't a foregone conclusion. With the right strategy and incentives, the ability for novel materials to be reused, recovered and recycled can be designed in at the outset*". If designers, manufacturers, material scientists and waste managers were to collaborate and develop new materials together, this would ensure end of life considerations were considered right from the start (Hazell, 2017). Moreover, including designers and engineers in the conversation could also help to locate new applications as the materials are developed, helping to uncover the real world use cases.

Lastly, this paper set out to explore how self-healing materials and the circular economy perspectives converge. As a result this study bridges the gap between material science and sustainability, and contributed insight to both in the following ways:

- Expands and consolidates academic and industrial perspectives for how and where self-healing materials might be utilised for longer lasting products

- Highlights the sustainability and circular economy factors that need to be considered when developing new self-healing materials

- Provides a roadmap for future research on how to advance self-healing materials and products

- Showcases the industrial perspective on the value and challenges for self-healing materials and products

6. Conclusion

In conclusion, this paper outlines an empirical study that investigated what are the benefits, opportunities, limitations and risks that self-healing materials pose to product lifetime extensions within the context of the circular economy. It was observed that the key benefits that self-healing can assist to: *maintain the primary lifetime of the product* from both a technical and service lifetime perspective; *refurbish and remanufacture of products* by potentially increasing the ease of disassembly and reassembly; and help to *enable alternative business models.* The key risks that must be considered are: *persistence* of these materials within the system*;* whether they belong to the *technosphere or biosphere? – hybridization of materials*; the *cycling of these materials* and whether this will create new waste streams or their value is worth recovering; the *technology development, performance and environmental trade-offs* that self-healing poses and lastly what issues might arise in regard to *compliance and liability*. These findings bridge the fields of self-healing materials and circular economy, by highlighting: which sustainability factors must be understood while developing novel self-healing compositions, expand our understanding for how these materials might be utilised to create longer lasting products and finally showcases the industry perspective on their challenges and contributions. Overall, while these self-healing materials may present challenges, their enhanced functionality offers exciting opportunities for innovation. Which could not only increase the lifespan of many types of products but also demonstrate more clearly the role that material innovation could play in product lifetime extension.

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References:

Aïssa, B., Therriault, D., Haddad, E., & Jamroz, W. (2012). Self-healing materials systems: Overview of major approaches and recent developed technologies. *Advances in Materials Science and Engineering, 2012*. https://doi.org/10.1155/2012/854203

Ackermann, L. (2018) ‘Design for Product Care: Enhancing Consumers’ Repair and Maintenance Activities’, *Design Journal.* 21(4), pp. 543–551. doi: 10.1080/14606925.2018.1469331.

Akrivos, V., Haines-Gadd, M., Mativenga, P., & Charnley, F. (2019). Improved metrics for assessment of immortal materials and products. *Procedia CIRP*, *80*, 596–601. https://doi.org/10.1016/j.procir.2018.12.012

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, *55*(3), 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Allione, C., De Giorgi, C., Lerma, B., & Petruccelli, L. (2012). From ecodesign products guidelines to materials guidelines for a sustainable product. Qualitative and quantitative multicriteria environmental profile of a material. *Energy*, *39*(1), 90–99. https://doi.org/10.1016/j.energy.2011.08.055

Al-Tabbaa, A., Litina, C., Giannaros, P., Kanellopoulos, A., & Souza, L. (2019). First UK field application and performance of microcapsule-based self-healing concrete. *Construction and Building Materials*, *208*, 669–685. https://doi.org/10.1016/j.conbuildmat.2019.02.178

Andrady, A. L. (2015) 'Persistence of Plastic Litter in the Oceans', in Bergmann, M., Gutow, L., and Klages, M. (eds) Marine Anthropogenic Litter. Cham: Springer International Publishing, pp. 57–72. doi: 10.1007/978-3-319-16510-3_3.

Ardente, F., & Mathieux, F. (2014). Environmental assessment of the durability of energy-using products: Method and application. *Journal of Cleaner Production*, *74*, 62–73. https://doi.org/10.1016/j.jclepro.2014.03.049

Autonomic Materials. (n.d.). AmpArmor | Autonomic Materials. Retrieved June 26, 2019, from https://www.autonomicmaterials.com/Our-Products

AutoScene. (2009). New self-healing clearcoat from AkzoNobel Car Refinishes features unrivalled gloss - Autoscene. Retrieved June 26, 2019, from https://www.autosceneuk.co.uk/new-self-healing-clearcoat-from-akzonobel-car-refinishes-features-unrivalled-gloss/

Bakker, C. A., & Schuit, C. S. C. (2017). *The Long View - Exploring Product Lifetime Extension*. UN Environment. https://doi.org/10.2307/2961837

Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: Exploring product life extension through design. *Journal of Cleaner Production*, *69*, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Bekas, D. G., Tsirka, K., Baltzis, D., & Paipetis, A. S. (2016). Self-healing materials: A review of advances in materials, evaluation, characterization and monitoring techniques. *Composites Part B: Engineering*, *87*, 92–119. https://doi.org/10.1016/j.compositesb.2015.09.057

Belleghem, B. V, Van den Heede, P., Tittelboom, K. V, De Belie, N.D., (2017). Quantification of the service life extension and environmental benefit of Chloride Exposed Self-Healing Concrete. *Materials (Basel*). 10. https://doi.org/10.3390/ma10010005

Benton, D., Coats, E., Hazell, J., 2015. A circular economy for smart devices: Opportunities in the US, UK, and India. Green Alliance.

Blaiszik, B. J., Kramer, S. L. B., Olugebefola, S. C., Moore, J. S., Sottos, N. R., & White, S. R. (2010). Self-Healing Polymers and Polymer Composites. *The Annual Review of Materials Research*. https://doi.org/10.1002/9781118082720

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Boddington, S., & Hubert, X. (2016). *White paper - Telepan*. Retrieved from http://www.teleplan.com/manage/wp-content/uploads/Teleplan_USED-EQUIPMENT-White-Paper-4.pdf

Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions - a strategy for eco-effective product and system design. *Journal of Cleaner Production*, *15*(13–14), 1337–1348. https://doi.org/10.1016/j.jclepro.2006.08.003

Braun, V. and Clarke, V. (2012) 'Thematic analysis, APA Handbook of Research Methods in Psychology', APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological. pp. 57–71. doi: 10.1037/13620-004.

Bridgens, B., & Lilley, D. (2017). Understanding material change: Design for appropriate product lifetimes. *Product Lifetimes and The Environment - PLATE 2017 Conference Proceedings - 8-10 November*, 54–59. https://doi.org/10.3233/978-1-61499-820-4-54

Chatterjee, A., Chattopadhyay, B., Mandal, S., 2019. Bacterium amended 100% fly ash geopolymer, in: AIP Conference Proceedings. Department of Physics, Jadavpur University, Kolkata, 700032, India. https://doi.org/10.1063/1.5127137

Continental. (n.d.). ContiSeal™. Retrieved June 26, 2019, from https://www.continental-tires.com/car/tires/continental-tire-technologies/contiseal

Cooper, T. (2010). The Significance of Product Longevity. In T. Cooper (Ed.), *Longer lasting products: alternatives to the throwaway society* (pp. 3–36). Gower.

Coillot, D., Méar, F. O., Podor, R., & Montagne, L. (2010). Autonomic self-repairing glassy materials. *Advanced Functional Materials*. https://doi.org/10.1002/adfm.201000147

Cordier, P. et al. (2008) 'Self-healing and thermoreversible rubber from supramolecular assembly', Nature, 451(7181), pp. 977–980. doi: 10.1038/nature06669.

Costea, A., Rardon, D. P., Padanilam, B. J., Fogel, R. I., & Prystowsky, E. N. (2008). Complications associated with generator replacement in response to device advisories. *Journal of Cardiovascular Electrophysiology*, *19*(3), 266–269. https://doi.org/10.1111/j.1540-8167.2007.01047.

Cseke, A., Haines-Gadd, M., Mativenga, P., Charnley, F. 'A Framework for Assessing Self-healing Products' 27th CIRP Life Cycle Engineering (LCE) Conference. Grenoble.

Das, R., Melchior, C., & Karumbaiah, K. M. (2016). Self-healing composites for aerospace applications. In *Advanced Composite Materials for Aerospace Engineering* (pp. 333–364). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100037-3.00011-0

Davies, R., Teall, O., Pilegis, M., Kanellopoulos, A., Sharma, T., Jefferson, A.,.. Lark, R. (2018). Large scale application of self-healing concrete: Design, construction, and testing. *Frontiers in Materials*, *5*(September), 1–12. https://doi.org/10.3389/fmats.2018.00051

Deloitte, (2019) *Wearables are on the rise, Retrieved 23 June, 2021, From:* https://www2.deloitte.com/be/en/pages/technology-media-and-telecommunications/topics/mobile-consumer-survey-2019/wearables.html

De Muynck, W., Debrouwer, D., De Belie, N., & Verstraete, W. (2008). Bacterial carbonate precipitation improves the durability of cementitious materials. *Cement and Concrete Research, 38*(7), 1005–1014. https://doi.org/10.1016/j.cemconres.2008.03.005

Den Hollander, M. C., Bakker, C. A. and Hultink, E. J. (2017) 'Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms', Journal of Industrial Ecology, 21(3), pp. 517–525. doi: 10.1111/jiec.12610.

Diesendruck, C. E., Sottos, N. R., Moore, J. S., & White, S. R. (2015). Biomimetic Self-Healing. *Angewandte Chemie - International Edition*, *54*(36), 10428–10447. https://doi.org/10.1002/anie.201500484

Du, P.; Liu, X.; Zheng, Z.; Wang, X.; Joncheray, T.; Zhang, Y. (2013) "Synthesis and characterization of linear self-healing polyurethane based on thermally reversible Diels-Alder reaction, *RSC Advances*, 3, pp. 15475–15482.

Ellen MacArthur Foundation (2013) Towards the Circular Economy: Economic and business rationale for accelerated transition vo1. doi: 10.1162/108819806775545321.

Ferguson, J. B., Schultz, B. F., & Rohatgi, P. K. (2014). Self-healing metals and metal matrix composites. *JOM*, *66*(6), 866–871. https://doi.org/10.1007/s11837-014-0912-4

Fifo, O., Ryan, K., & Basu, B. (2015). Application of Self-Healing Technique to Fibre Reinforced Polymer Wind Turbine Blade. *Smart Structures and Systems*, *16*(4), 593–606.

Gao, J., Kim, H., Kim, J., Kwak, J.B., 2019. Enhancing cover glass fracture resistance for hand-held devices with PEALD-based Al2O3 coating. Ceram. Int. 45, 19496–19503. https://doi.org/https://doi.org/10.1016/j.ceramint.2019.06.207

Geissdoerfer, M. et al. (2017) 'The Circular Economy – A new sustainability paradigm?', Journal of Cleaner Production. Elsevier Ltd, 143, pp. 757–768. doi: 10.1016/j.jclepro.2016.12.048.

Ghosh, S. K. (2009). *Self-Healing Materials*. *Self-Healing Materials: Fundamentals, Design Strategies, and Applications*. Wiley. https://doi.org/10.1002/9783527625376.ch5

Gordon, K. L., Siochi, E. J., Yost, W. T., Bogert, P. B., Howell, P. A., Cramer, K. E., & Burke, E. R. (2017). *Ballistic Puncture Self-Healing Polymeric Materials*. NASA Langley Research Center; Hampton, VA, United States. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20170007198

Gov.Net (2020) Guidance - CE Marking. Available at: https://www.gov.uk/guidance/ce-marking (Accessed: 18 May 2020).

Grand Review Research. (2017). Self-healing Materials Market Worth $4.1 Billion By 2025 | CAGR: 27.2%. Retrieved June 26, 2019, from https://www.grandviewresearch.com/press-release/global-self-healing-materials-market

Grande, A. M. et al. (2013) 'Rate-dependent self-healing behavior of an ethylene-co-methacrylic acid ionomer under high-energy impact conditions', Journal of Applied Polymer Science. doi: 10.1002/app.39384.

Guadagno, L. et al. (2014) 'Self-healing materials for structural applications', Polymer Engineering and Science. doi: 10.1002/pen.23621.

Gurova, O., Merritt, T.R., Papachristos, E., Vaajakari, J., 2020. Sustainable solutions for wearable technologies: Mapping the product development life cycle. Sustain. 12, 1–26. https://doi.org/10.3390/su12208444

Hager, M. D., Greil, P., Leyens, C., Van Der Zwaag, S., & Schubert, U. S. (2010). Self-healing materials. *Advanced Materials*, *22*(47), 5424–5430. https://doi.org/10.1002/adma.201003036

Heng, X. et al. (2015) 'Reduced radiation damage in a multicomponent phosphate glass by Nb 5 + or Sb 3 + doping', 5(10), pp. 2272–2280. doi: 10.1364/OME.5.002272.

Herbert, E. N., & Li, V. C. (2013). Self-healing of microcracks in engineered cementitious composites (ECC) under a natural environment. *Materials*, *6*(7), 2831–2845. https://doi.org/10.3390/ma6072831

Hia, I. L., Vahedi, V., & Pasbakhsh, P. (2016). Self-Healing Polymer Composites: Prospects, Challenges, and Applications. *Polymer Reviews*, *56*(2), 225–261. https://doi.org/10.1080/15583724.2015.1106555

HIT-USA. (2019). *BATTLEJACKET ®*. Retrieved from https://www.hit-usa.com/BattleJacket-sell-sheet.pdf#

IFixit (2020) Right to repair: Repairable Products. Available at: https://www.ifixit.com/Right-to-Repair/Repairable-Products (Accessed: 16 January 2020).

Imperial Motion. (n.d.). Nano Cure Tech. Retrieved June 26, 2019, from https://imperialmotion.com/collections/nano-cure-tech

Kang, J., Tok, J.B., Bao, Z., 2019. Self-healing soft electronics. Nat. Electron. 2. https://doi.org/10.1038/s41928-019-0235-0

Kaplani, E. (2012) 'Detection of degradation effects in field-aged c-Si solar cells through IR thermography and digital image processing', International Journal of Photoenergy, 2012. doi: 10.1155/2012/396792.

Kirchherr, J., Reike, D. and Hekkert, M. (2017) 'Conceptualizing the circular economy: An analysis of 114 definitions', *Resources, Conservation and Recycling*. 127, pp. 221–232. doi: 10.1016/j.resconrec.2017.09.005.

Kim, D., Hyun, S. and Han, S. M. (2018) 'Freestanding silicon microparticle and self-healing polymer composite design for effective lithiation stress relaxation', *Journal of Materials Chemistry A*, 6 (24), pp. 11353–11361. doi: 10.1039/c7ta11269f.

Kim, Y., Nam, K.-H., Jung, Y.C., Han, H., 2020. Interfacial adhesion and self-healing kinetics of multi-stimuli responsive colorless polymer bilayers. Compos. Part B Eng. 203, 108451. https://doi.org/https://doi.org/10.1016/j.compositesb.2020.108451

Lindahl, P., Robèrt, K., Ny, H., & Broman, G. (2014). Strategic sustainability considerations in materials management. *Journal of Cleaner Production*, *64*, 98–103. https://doi.org/10.1016/j.jclepro.2013.07.015

Linder, M. and Williander, M. (2017) 'Circular Business Model Innovation: Inherent Uncertainties', *Business Strategy and the Environment*, 26(2), pp. 182–196. doi: 10.1002/bse.1906.

Lizasoain-Arteaga, E., Indacoechea-Vega, I., Pascual-Muñoz, P., Castro-Fresno, D., 2019. Environmental impact assessment of induction-healed asphalt mixtures. J. Clean. Prod. 208, 1546–1556. https://doi.org/10.1016/j.jclepro.2018.10.223

Lewandowski, M. (2016) 'Designing the business models for circular economy-towards the conceptual framework', Sustainability (Switzerland), 8(1), pp. 1–28. doi: 10.3390/su8010043.

Mauldin, T. C., & Kessler, M. R. (2010). Self-healing polymers and composites. *International Materials Reviews*, *55*(6), 317–346. https://doi.org/10.1179/095066010x12646898728408

Markvicka, E. J. et al. (2018) 'An autonomously electrically self-healing liquid metal–elastomer composite for robust soft-matter robotics and electronics', Nature Materials. Springer US, pp. 1–7. doi: 10.1038/s41563-018-0084-7.

McDonough, W., & Braungart, M. (2002). Cradle to cradle: remaking the way we make things. New York: North Point Press.

Merli, R., Preziosi, M. and Acampora, A. (2018) 'How do scholars approach the circular economy? A systematic literature review', Journal of Cleaner Production. Elsevier Ltd, 178, pp. 703–722. doi: 10.1016/j.jclepro.2017.12.112.

Mintel, (2018) Smashing times: 24% of smartphone owners have broken their screen in the past two years, Retrieved 23 June, 2021, From: https://www.mintel.com/press-centre/technology-press-centre/smashing-times-24-of-uk-smartphone-owners-have-broken-their-screen-in-the-past-two-years?ref=hackernoon.com

Montalvo, C., Peck, D. and Rietveld, E. (2016) 'A Longer Lifetime for Products: Benefits for Consumers and Companies', Study for Internal Market and Consumer Protection (IMCO). doi: www.europarl.europa.eu/studies.

Moreno, M. et al. (2016) 'A conceptual framework for circular design', Sustainability (Switzerland), 8(9). doi: 10.3390/su8090937.

Nasa, (n.d*) Self-healing wire insulation. Retrieved 23 June, 2021, From: https://technology.nasa.gov/patent/KSC-TOPS-51*

Nes, N. Van, & Cramer, J. (2005). Product lifetime optimization : a challenging strategy towards more sustainable consumption patterns, *14*, 1307–1318. https://doi.org/10.1016/j.jclepro.2005.04.006

Nei Corporation (2020) *Self-healing coatings*. Available at: https://www.neicorporation.com/products/coatings/self-healing-coatings/ (Accessed: 21 May 2020).

Nissan Motor Corporation. (n.d.). Scratch Shield | NISSAN | TECHNOLOGICAL DEVELOPMENT ACTIVITIES. Retrieved June 26, 2019, from https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/scratch.html

Nußholz, J. L. K. (2017). Circular business models: Defining a concept and framing an emerging research field. *Sustainability (Switzerland)*, *9*(10), 14–17. https://doi.org/10.3390/su9101810

Pamulapati, Y., Elseifi, M. A., Cooper, S. B., Mohammad, L. N., & Elbagalati, O. (2017). Evaluation of self-healing of asphalt concrete through induction heating and metallic fibers. *Construction and Building Materials*, *146*, 66–75. https://doi.org/10.1016/j.conbuildmat.2017.04.064

Prakash, S., Dehoust, G., Gsell, M., Schleicher, T. and Stamminger, R. (2016) Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz". Dessau- Roßlau: Umweltbundesamt Wörlitzer Platz. Available at: https://www.umweltbundesamt.de/en/publikationen/einfluss-der-nutzungsdauer-von- produkten-auf-ihre-1.

Prendeville, S., O'Connor, F., & Palmer, L. (2014). Material selection for eco-innovation: SPICE model. *Journal of Cleaner Production*, *85*, 31–40. https://doi.org/10.1016/j.jclepro.2014.05.023

Oghazi, P. and Mostaghel, R. (2018) 'Circular business model challenges and lessons learned-An industrial perspective', Sustainability (Switzerland), 10(3), pp. 1–19. doi: 10.3390/su10030739.

Tecchio, P. et al. (2017) 'In search of standards to support circularity in product policies: A systematic approach', Journal of Cleaner Production. Elsevier Ltd, 168, pp. 1533–1546. doi: 10.1016/j.jclepro.2017.05.198.

Rigamonti, S., Cuenca, E., Arrigoni, A., Dotelli, G., Ferrara, L., 2019. Self-healing concrete vs. Conventional waterproofing systems in underground structures: A cradle to gate LCA comparison with reference to a case study, in: Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018. Politecnico di Milano, Milano, Italy, pp. 2277–2284.

Roberts, C. (2015) Novel materials - new opportunities and new challenges for the Circular Economy, Journal of the Institution of Environmental Sciences. London. Available at: https://www.the-ies.org/sites/default/files/journals/ES_March2015_new-materials.pdf.

Rong, et al. (2017) 'Anti-freezing, Conductive Self-healing Organohydrogels with Stable Strain-Sensitivity at Subzero Temperatures', Angewandte Chemie - International Edition. doi: 10.1002/anie.201708614.

Sarkar, M., Adak, D., Tamang, A., Chattopadhyay, B., & Mandal, S. (2015). Genetically-enriched microbe-facilitated self-healing concrete-a sustainable material for a new generation of construction technology. *RSC Advances*, *5*(127), 105363–105371. https://doi.org/10.1039/c5ra20858k

Schlangen, E., & Sangadji, S. (2013). Addressing infrastructure durability and sustainability by self healing mechanisms - Recent advances in self healing concrete and asphalt. *Procedia Engineering*, *54*, 39–57. https://doi.org/10.1016/j.proeng.2013.03.005

Singh, R. N. (2014). Kinetics of self-repair in inorganic glasses: Modeling and experimental verification. *Journal of Materials Science*, *49*, 4869–4879. https://doi.org/10.1007/s10853-014-8188-1

Slime products. (n.d.). Self-Sealing Bicycle Tubes | Slime – Slime Products. Retrieved June 26, 2019, from https://shop.slime.com/collections/self-sealing-bicycle-tubes

Stahel, W. (2010). *The Performance Economy* (2nd ed.). Palgrave Macmillan.

Stahel, W. R. (2013). Policy for material efficiency - Sustainable taxation as a departure from the throwaway society. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(1986). https://doi.org/10.1098/rsta.2011.0567

Stemler, Steve (2000) "An overview of content analysis," Practical Assessment, Research, and Evaluation: Vol. 7, Article 17. DOI: https://doi.org/10.7275/z6fm-2e34

Su, J. F., Han, S., Wang, Y. Y., Schlangen, E., Han, N. X., Liu, B., … Li, W. (2017). Experimental observation of the self-healing microcapsules containing rejuvenator states in asphalt binder. *Construction and Building Materials*, *147*, 533–542. https://doi.org/10.1016/j.conbuildmat.2017.04.190

Tukker, A. (2015) Product services for a resource-efficient and circular economy - A review, *Journal of Cleaner Production.* 97, pp. 76–91. doi: 10.1016/j.jclepro.2013.11.049.

Tao, X., Xu, X., Xu, X., Hong, W., Guo, A., Hou, F., & Liu, J. (2017). Self-healing behavior in MoSi2/borosilicate glass composite. *Journal of the European Ceramic Society*, *37*(2), 871–875. https://doi.org/10.1016/j.jeurceramsoc.2016.08.043

Van den Heede, P., Mignon, A., Habert, G., De Belie, N., 2018. Cradle-to-gate life cycle assessment of self-healing engineered cementitious composite with in-house developed (semi-)synthetic superabsorbent polymers. Cem. Concr. Compos. 94, 166–180. https://doi.org/10.1016/j.cemconcomp.2018.08.017

Van den Heede, P., De Belie, N., Pittau, F., Habert, G., Mignon, A., 2019. Life cycle assessment of self-healing engineered cementitious composite (SH-ECC) used for the rehabilitation of bridges, in: Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018. Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering and Architecture, Ghent University, Ghent, Belgium, pp. 2269–2275.

Van Nes, N. and Cramer, J. (2005) 'Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns', 14, pp. 1307–1318. doi: 10.1016/j.jclepro.2005.04.006.

Vanegas, P. et al. (2018) 'Ease of disassembly of products to support circular economy strategies', Resources, Conservation and Recycling, 135(July 2017), pp. 323–334. doi: 10.1016/j.resconrec.2017.06.022.

Wang, C., Wu, H., Chen, Z., Mcdowell, M. T., Cui, Y., & Bao, Z. (2013). Self-healing chemistry enables the stable operation of silicon microparticle anodes for high-energy lithium-ion batteries. *Nature Chemistry*, *5*(12), 1042–1048. https://doi.org/10.1038/nchem.1802

Wang, J., Kato, K., Blois, A. P., & Wong, T. S. (2016). Bioinspired Omniphobic Coatings with a Thermal Self-Repair Function on Industrial Materials. *ACS Applied Materials and Interfaces*. https://doi.org/10.1021/acsami.6b00194

Wang, Y. et al. (2018) Stretchable, Conductive, and Self-Healing Hydrogel with Super Metal Adhesion, Chemistry of Materials. *American Chemical Society*, 30(13), pp. 4289–4297. doi: 10.1021/acs.chemmater.8b01260.

Webster, K. (2017). *The Circular Economy: A Wealth of Flows* (1st ed.). Isle of Wight: Ellen MacArthur Foundation Publishing.

White, S. R., Moore, J. S., Sottos, N. R., Krull, B. P., Santa Cruz, W. A., & Gergely, R. C. R. (2014). Restoration of large damage volumes in polymers. *Science*, *344*(6184), 620–623. https://doi.org/10.1126/science.1251135

Wiktor, V., & Jonkers, H. M. (2016). Bacteria-based concrete: From concept to market. *Smart Materials and Structures*, *25*(8). https://doi.org/10.1088/0964-1726/25/8/084006

Williams, G.; Bond, I.; Trask, R. (2009) Compression after impact assessment of self-healing CFRP, Composites Part A: Applied Science and Manufacturing 2009, 40, 1399–1406.

Wood C.D, and Green, P.A, (2016) Method and Device for Detecting Fascia Damage and Repairing the Same, U.S. Patent no. US 2017/0228.094A1) U.S Patent Trademark Office, Retrieved 23 June, 2021, from: https://patentimages.storage.googleapis.com/25/e2/b6/15cad3c5fb7c91/US20170228094A1.pdf

Wool, R. P. (2008) 'Self-healing materials: A review', Soft Matter, 4(3), pp. 400–418. doi: 10.1039/b711716g.

Wong, T. S. et al. (2011) Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity, *Nature*. doi: 10.1038/nature10447.

Wu, S., Li, J., Zhang, G., Yao, Y., Li, G., Sun, R., & Wong, C. (2017). Ultrafast Self-Healing Nanocomposites via Infrared Laser and Their Application in Flexible Electronics. *ACS Applied Materials & Interfaces*. https://doi.org/10.1021/acsami.6b15476

Yang, W. (2013). Testing and Condition Monitoring of Composite Wind Turbine Blades. In *Recent Advances in Composite Materials for Wind Turbines Blades* (pp. 147–169). Hong kong.

Xu, S., Tabaković, A., Liu, X., & Schlangen, E. (2018). Calcium alginate capsules encapsulating rejuvenator as healing system for asphalt mastic. *Construction and Building Materials*, *169*, 379–387. https://doi.org/10.1016/j.conbuildmat.2018.01.046

Zhang, Y.; Broekhuis, A. A.; Picchioni, F. (2009) "Thermally self-healing polymeric materials: the next step to recycling thermoset polymers?", Macromolecules, 42, 1906–1912

Zhang, L., Dong, X. and Zhang, H. (2009) 'Application research on self-healing technology with microcapsules for automobile brake pad', Journal of Wuhan University of Technology-Material Science Edition, 24(1), pp. 91–94. doi: DOI 10.1007/s11595-009-1091-y.

Zeng, C.; Seino, H.; Ren, J.; Hatanaka, K.; Yoshie, N. "Bio-based furan polymers with self-healing ability", Macromolecules 2013, 46, 1794–1802

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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