

Advances in Linseed Oil-Filled Microcapsules for Self-Healing Coatings: Preparation, Characterization, Healing Mechanisms, Performance and Future Perspectives

Mohd Fauzi bin Mamat^{1, 2*}, Mohd Warikh bin Abd Rashid^{1, 2}, Lailatul Harina binti Paijan^{1, 2}, Mohd Hadzley bin Abu Bakar^{1, 2}, Mohammad Rhadhi Kamshah^{1, 3} and Nor Ana Rosli¹

¹Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Kampus Teknologi, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

²Centre of Smart System and Innovative Design (COSSID UTeM), Universiti Teknikal Malaysia Melaka (UTeM), Kampus Teknologi, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

³Department of Occupational Safety and Health (DOSH/JKKP), Wilayah Persekutuan Kuala Lumpur, Aras 10 & 11 (West Wing), The ICON, No. 1, Jalan 1/68F, Jalan Tun Razak, 50534 Kuala Lumpur, Malaysia.

*Corresponding author

DOI: <https://doi.org/10.47772/IJRISS.2026.1026EDU0620>

Received: 19 September 2026; Accepted: 24 September 2026; Published: 08 October 2026

ABSTRACT

Drying oils such as linseed oil are interesting the attention of researchers not only as paint protection but also as self-healing components in smart coatings for corrosion protection. Linseed oil due to the fast-drying properties when they contact oxygen from the atmosphere. The encapsulation method is a quick and easy way to sanctuary their properties, facing many challenges in achieving stable oil-in-water emulsions. Linseed oil filled urea-formaldehyde microcapsules with various sizes were prepared via in-situ polymerization. To recognize the healing performance of linseed oil as a healing agent and the development of corrosion processes underneath the healed area, long term corrosion performing of scratched epoxy-based coating samples containing microcapsules. This review paper summarizes recent accomplishments in encapsulating linseed oils, tackling their high viscosity by changing process parameters (stirring speed, homogenization/ultrasonic step, use of different emulsifiers, etc.). This review paper also delivers a cheap and feasibility analysis for the industrial application of drying oils in self-healing coatings for corrosion protection. Corrosion test results showed that although linseed-oil can significantly improve the corrosion performance of the damaged coating in short-term however it rapidly decreases with time and hence this should be taken into account in designing of microcapsule's core composition.

Keywords: linseed oil, microcapsule, self-healing coating, corrosion protection

INTRODUCTION

The cost of corrosion protection methods are related to the coating material [1]. Coatings exposed to mechanical, chemical or thermal stress can lead to the degradation of their physical properties which enhance the failure of coating material (Figure 1 (a)) [2, 3-4]. These failures, which diminish the life and protective properties of coatings, reduce the life of protected structure or equipment, because in addition to local corrosion, recoating requires surface preparation and thickness loss [1]. The ability and success of self-healing materials to retain functionalities and restore the structural integrity autonomously after an eventual failure/damage caused by a mechanical injury, enhance the lifetime and durability that trigger the coating containing embedded liquid monomer microcapsules [5, 6-9]. Once the damage is presented, these microcapsules release the agent and heal the fracture as displayed in Figure 1 (b).

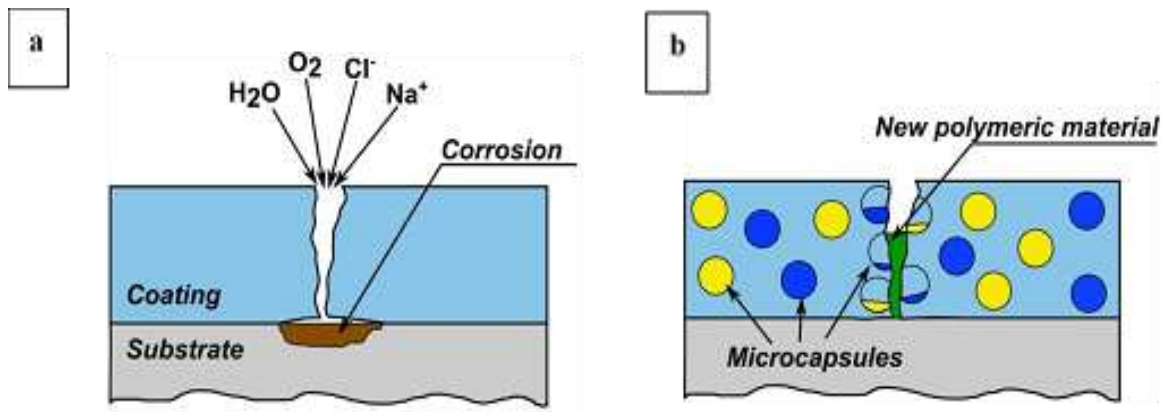


Figure 1. (a) The failure of coating and (b) self-healing mechanism in microcapsule based coating [3].

Similar to the biology where proteins, platelets and other components from the blood are recruited to the damaged skin, healing agents are incorporated into a polymer, and are drawn to damage in polymers, polymerizing to form new material in the damaged region [2]. In the recent years, the interest in self-healing coating has witnessed strong growth and its successful laboratory design, modification and synthesis provided a suitable base for achieving smart and multi-functional materials [2 -10]. In service, the damage regions are exposed to the environment, which assisted the corrosion problems. Thus, the self-healing coating shows great potential for solving the limiting problem of polymer coating such as internal damage and micro-cracks [2-20].

TYPES OF SELF-HEALING COATING

Protective polymeric coating is the most universal and command strategy to protect metals from corrosion issues. During service, once the coating is damaged and failed, autonomous repair of the damage due to the self-healing coating strategy increases the coating lifetime and reduces the cost [21-22]. In the self-healing research area, two common of self-healing coating strategies for coating materials were the extrinsic self-healing coating, usually autonomic or capsule-based systems [20-36] incorporated with polymer matrix. In contrast, intrinsic self-healing [22, 37] depends on the physical, chemical or molecular interaction of polymer matrix. The intrinsic systems achieve the ability of molecular bonds curable via the heat (metal-ligand bonding, covalent bonding), light (ultraviolet or IR radiation), mechanical and chemical source [19].

The autonomic or capsule-based healing systems have been implemented and are used for a wide range of coating materials and applications [22]. In this method, healing agents are encapsulated (micro/nano size) with shell-core as paint additive and dispersed in a matrix such as epoxy based polymer coating easily through blending techniques. When damage occurs, the capsules rupture, releasing their contents (healing agent) into the damaged region [22, 37]. Both strategies have advantages and disadvantages based on the application and properties that were reviewed in the current research area.

Concept of Autonomic Self-Healing Coating

Several self-healing coating strategies have been studied, and the most successful and versatile approach utilizes embedded microcapsules that are filled with a liquid healing agent in coating structure [2-10]. White et al. [2] demonstrated a self-healing system where healing agents are incorporated into polymer as capsules or particles in Figure 2 [38]. As a crack propagates through the polymer matrix, the healing agents release into the crack plane, mix, and form new polymer. The healing agent material, usually in liquid phase, is stored in special spaces through the material body and are covered by the shell structure. After tearing of the space wall due to the matrix scratch or crack, the stored healing agent releases and the scratch is repaired by polymerization process. In this system, the healant material is stored through the almost equal sized capsules [2, 39].

Micro/nano capsule embedment through the polymer matrix was the main approach for self-healing ability in coatings. Figure 2 (a) showed a representative schematic of self-healing process of this approach. Currently, the research environment on this area was implemented the user or industrial idea and perspective as demonstration in Figure 2 (b) the principle of self-healing material starting from the design and preparation, the main issues

must be addressed and current technology was implement and the output are presented. The achievements and progress since the innovative work by White et al. in 2001 [2] showed that the application will contribute to the continuing development of new self-healing material systems [37].

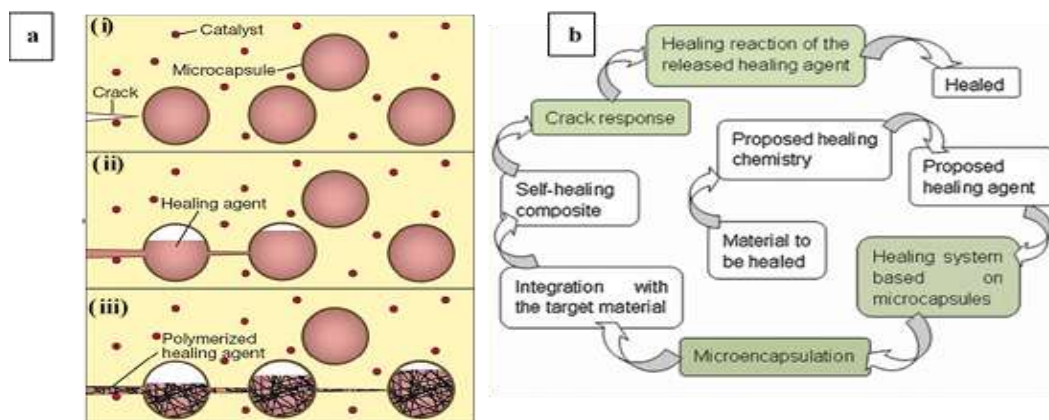


Figure 2. (a) Concept of the autonomic mechanically triggered healing into a polymer matrix; (i) Crack form propagates through the polymer coating (ii) the crack ruptures the microcapsules, releasing the healing agent into the crack plane through capillary action and when the healing agent meets catalyst in the polymer, it polymerizes creating new polymer and closes the damage (iii) Figure adapted from [2] and (b) Flowchart of imparting self-healing capabilities to polymeric materials using microencapsulated healing agents [37].

Self-Healing Coating Preparation and Mechanism

In recent years, with continuous research and development of surface engineering, the demand for self-healing coating as the new smart materials is growing rapidly which can provide some outstanding of the properties of polymeric coatings. In this regard, the first study and exploration on stimuli-responsive healable materials was published early in 1990s [35]. Table 1 presented the literature survey of selected papers on the area of self-healing coating development based on the different recipes and formulation for different aims and applications.

Table 1 Details of microencapsulation methods and synthesis done by many researcher.

Author/ Year	Shell material	Core material (healing agent)	Finding
Suryanarayana <i>et al.</i> [33] - 2008	Poly-urea-formaldehyde (PUF)	Linseed oil	The cracks in a paint coating were successfully healed when linseed oil was released from microcapsules ruptured. Linseed oil healed area was found as good candidates to prevent corrosion of the substrate.
Sinou Lang <i>et al.</i> [32] -2017	Poly-urea-formaldehyde (PUF)	Linseed oil	Cross section of coating shows the uniform distribution of microcapsules and the high content of core materials ensured the self-healing function more than 82%. The self-healing coating showed excellent healing performance upon artificial cracks at coating surface.
Dawei Sun <i>et al.</i> [13] -2016	Poly-urea-formaldehyde (PUF)	Methylene cyclohexane diisocyanate (HDMI)	The scratched self-healing coatings was successful or functionality and satisfactory anticorrosion performance in salt water In addition, after immersion in ambient water for 30 days still possessed superior anticorrosion performance.
Barbara Di Credico <i>et al.</i> [18] -2013	PU/ Poly-urea-formaldehyde (PUF)	Isophorone diisocyanate (IPDI)	The new synthesis of double layered PU/PUF microcapsules filled with IPDI were spherical with rough outer surface to ensure a good adhesion with a polymeric matrix. The IPDI content (50–70%) per capsule.
Haiyan Li <i>et al.</i> [299] -2017	Polysulfone (PSF)	Tung oil	10 wt% microcapsules embedded in epoxy coating offered optimum results. The self-healing coating showed excellent

			anticorrosion performance due to formation of a cross-linked polymer film after tung oil was released. The frictional coefficient and wear rate of the self-lubricating coating decreased significantly for tribology performance.
Seyed Fakhreddin Hosseini <i>et al.</i> [46] -2013	Chitosan nanoparticles	Oregano oil	The final particles were spherical in shape with size range 40–80nm. The content of OEO in the nanoparticles influenced its release rate from the chitosan nanoparticles.

The earliest practical benchmark demonstration of self-healing materials was introduced by White et al. in 2001 [2] and 2003 [40], with the formulation of urea–formaldehyde (UF) microcapsules containing dicyclopentadiene (DCPD) as the healing agent used to offer self-healing coating to an epoxy-based composite. The mechanism of repairing the failure/damaged has been achieved through the ring opening polymerization of DCPD in the presence of a Grubbs' catalyst, also known as two component epoxy hardener [3, 5, 133, 14-19, 35, 42, 44]. When the stress-induced crack reached the microcapsules, the healing agent was released within the crack lines and came into contact with the active materials, thus polymerization started and the damage was repaired [14-19, 35]. Although this approach is one the most promising for successful self-healing materials, Grubbs' catalysts are expensive and could be deactivated [35].

Addressing these issues, several researchers have proposed new materials to solve the problem to synthesise core material such as plant/ drying oil, epoxy resin and reactive solvent [35]. Among the new materials, drying oils such as linseed, tung, oregano and coconut oil were the cheapest eco-friendly materials widely used in coating industry and the best candidates for healing agent in self-healing coatings [25-36]. Suryanarayana et al. [33] microencapsulated linseed oil with PUF shell. After that, Hatami Boura et al. [34] prepared nanocapsules containing linseed oil and compared its self-healing performance. During the synthesis technique, selection of parameter was important in the optimization of shell: core, for excellent mechanism in coating matrix.

The healing property of microcapsules strongly depends on their final size. The loading efficiency of the healing materials has been reported [21]; however, the limitation of coating applications such as coating thickness, types of capsule and matrix materials properties must also be considered. Therefore, one hypothesis is that the optimization of size distribution and loading of microcapsules embedded in polymer matrix is the key element to the successful preparation of a self-healing coating [21]. White et al. [40] suggested that the size of microcapsules should be ideally smaller than the dry thickness of the self-healing coating. However, smaller microcapsules reveal less efficiency at lower concentrations; therefore, higher microcapsule concentrations are required for enhancing self-healing performance [31, 32, 40]. It is also reported that a larger amount of agent present in the microcapsules gave better repairing properties to the coating matrix [21, 31]. In addition, Sinou Lang et al. [32] indicated that the microcapsule surface will cause coalescence between them, enhancing the heavy agglomeration of microcapsules, while at the same time leading to poor dispersion of microcapsules while they are embedded in the coating matrix. Moreover, the agglomeration of microcapsules in coating will create low healing efficiency because of the non-uniform distribution of microcapsules [32].

The concentration of the microcapsules size and loading strongly affected the self-healing capability and performance [165]. Specific to corrosion resistance performance, the self-healing containing 10wt. % [8, 16, 17, 29, 33], 15wt. % [5, 18], and 20wt. % [14] microcapsules showed superior protection based on the microcapsule size and the damage scale. The increasing of microcapsule concentration may lead the frictional coefficient and wear rate to gradually increase. This phenomenon was attributed to the decreased mechanical properties with increasing microcapsule content, which were reported in our previous study [32].

The self-healing performance of the coatings was evaluated by corrosion test through immersion, salt spray and electrochemical test. The scratched or crack area was made at the self-healing coating surface to study the self-healing property [17]. The SEM images illustrated the newly formed materials filled the crack. The crack was in this way sealed and healed autonomously generated by the rupture of healing agent as displayed in Figure 3. The concentration of microcapsules of 10wt. %, showed the excellent corrosion-protection performance, was presented by Haiyan et al. [29]. Behzadnasab et al. [31], who reported that the EIS and salt spray corrosion tests showed that coating layers containing these linseed oil microcapsules exhibited self-healing characteristics at optimum microcapsule loading. Development of HDI was encapsulated to develop self-healing anticorrosive

coatings. The self-healing performance and evaluation of their anticorrosion property through salt spray test exhibited excellent corrosion resistant and by EIS measurement, and the results revealed the formation and increment of a new film formed enhanced the excellent protection that was done by Mingxing et al. [14, 44].

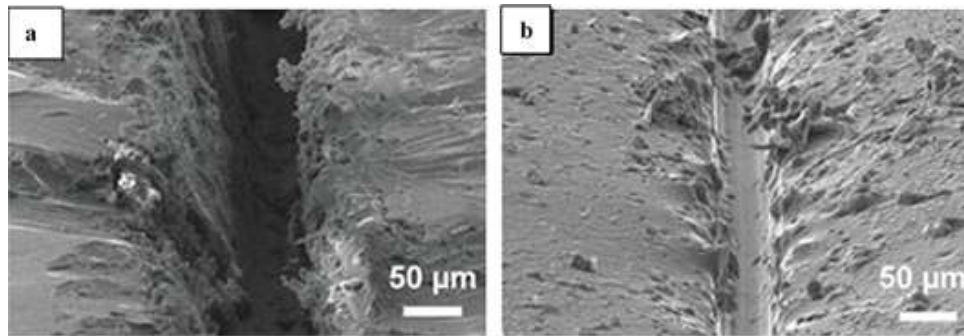


Figure 3 SEM images of the scribed regions of corrosion and morphological evaluation of self-healing coatings, consisting of matrix, adhesion promoter, microencapsulated catalyst, and phase-separated PDMS healing agent; (a) the control coating and (b) the self-healing coating after healing [47].

Van Benthem et al. [39] proposed a classification of damage, which is macro, micro and nano, according to their scale as displayed in Table 2. The classification is very important as the implementation of healing mechanism will depend on the scale of failure and the microcapsule size to supply sufficient amount to heal the damage [39]. A study by Yabuki et al. [8] mentioned the optimal concentration of SAP in the middle layer for the self-healing capability was 5-10wt. % to heal 6mm length of scratch. The polarization result showed the time was increased, resulting in the inhibition capability of SHC. 5wt. % of microcapsules in paint films released the healing material, which healed cracks efficiently with size 60 and 116.5 µm width and depth. This result, which enhanced the satisfactory anticorrosion properties through the increasing total impedance (|Z|) from EIS test, was proposed by Liao et al. [5].

Table 2 Damage-scale classification [2].

Scale	Level affected	Type of damage
Macro	Coating Interface	Delamination rupture, flaking scratches, pin holes, porosities
Micro	Networks	Microcracks
		Cavitation
		Crazing
Nano	Molecules Bonds	Dissociation
		Bond breakage

Mirocapsulation Techniques and Properties of The Capsules

The investigation is carried out on a system utilising mechanical stimulus, which judging from the number of recent publications [10], seems to be the most pursued route to truly autonomous self-healing coatings. The method is based on the incorporation of microcapsules uniformly distributed into a polymer matrix keeping, the healing agent in a “trapped” state, and the core material leading to spontaneous leakage [3]. Microcapsules are spherical, sometimes elongated [3] particles with diameters of 3-800 µm depending on the application and consists of 10 – 90wt. % core material. As illustrated in Figure 4, the capsules consist of a solid droplet of liquid or gasses covered by an outer layer of shell material. The final microcapsule diameter is influenced by a combination of several parameters including the geometry of the temperature, agitation rate, mixing device, viscosity of the reaction media, surfactant concentration and others [42].

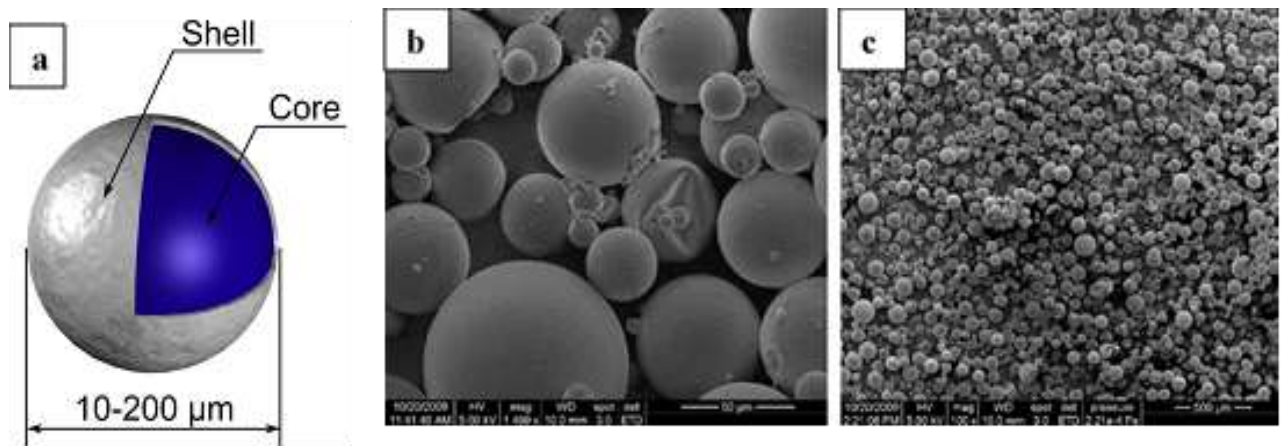


Figure 4 (a) Schematic drawing of a microcapsule and (b and c) SEM micrograph of poly(melamine-urea-formaldehyde) microcapsules filled with alkylglycidyl ether. Both pictures were taken 1.5 months after the synthesis was performed [3].

Microencapsulation of a healing agent is a process where the agent's droplets are covered with a thin film of a shell material. In situ polymerization [2, 4-8, 14-21] or oil-in water emulsion polymerization [10, 14, 15, 46] and inter polymerization [3, 14, 46], coacervation, solvent evaporation [29] and sol-gel methods were several techniques and command methods for synthesis of the microcapsules. These marked the processes within other methods and in situ polymerization can be chosen as the most relevant to synthesize the capsule because of low cost, ease, very fast and it does not require high level technology to produce the capsule as demonstrated in Figure 2.17 and process of in-situ polymerization method by Brown et al. [4, 44]. That is why more than 80% of research in self-healing coatings areas has been selected the in-situ polymerization as a major procedure for fabrication of microcapsule as shown earlier in this paragraph.

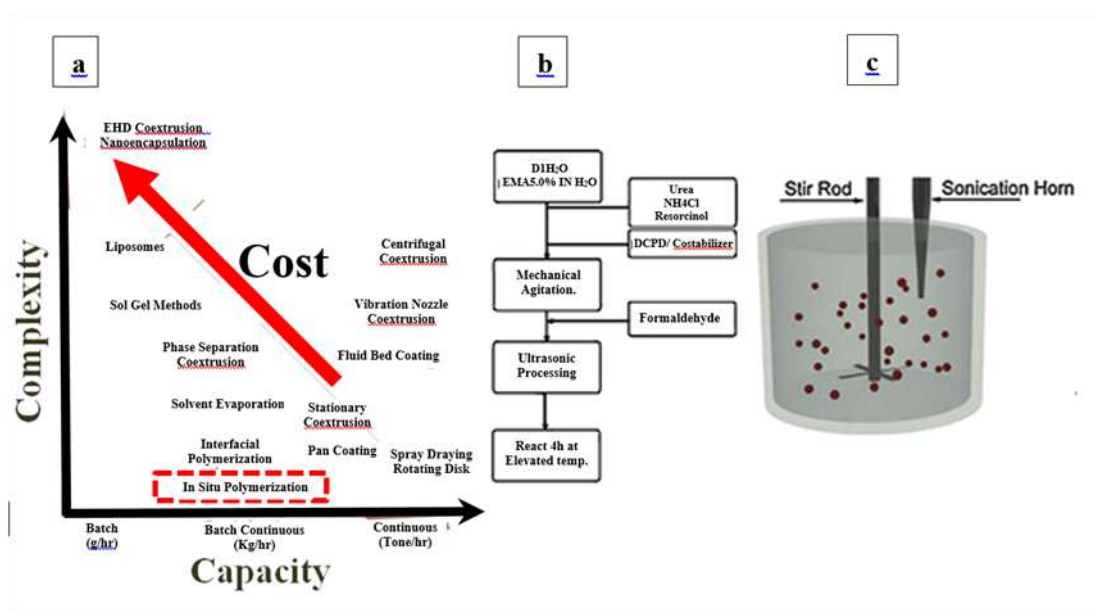


Figure 5 (a) Comparison between the different encapsulation methods and capsulation method for preparing UF capsules containing DCPD using sonication. (b) Process flow chart; (c) Schematic showing the emulsion prior to sonication [3].

The generalized scheme of in-situ encapsulation process can be seen from Figure 6 as example of dicyclopentadiene capsule creation [41]. Although the process during synthesis to meet the requirements looks very simple, care of parameters of the synthesis process must be taken as it affects their yield and eventual properties. The ability to keep capsulated material for a long time, yet with the ability to rupture readily when the polymer is damaged, is the most important characteristic. As added value the capsules remain intact during coating formulation and application and produce a high adhesion to the polymer matrix [41]. The very high loading of active agent is the main advantage of the in-situ polymerization approach [40].

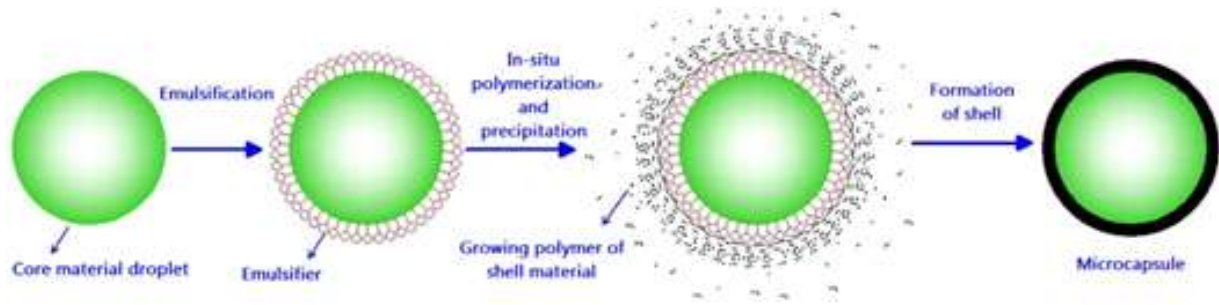


Figure 6 Schematic drawing of the formation of microcapsules by in situ polymerization [53].

In the previous literature there are several researches on the preparation of shell material microcapsule through the various chemical formulation. Mostly the common shell materials chosen are the poly-urea-formaldehyde (PUF) [2, 4-10, 14, 17-20, 49], poly-methylmethacrylate (PMMA) [139], methacrylate (MMA)-butylacrylate (BA)-methacrylic acid (MA) [16], double wall PU/PUF [18] and melamine-urea-formaldehyde [42]. Surprisingly, from the previous and current research area, poly urea-formaldehyde (PUF) was the prevalent shell material of the synthesized micro/nano capsules, but various core material (healing agent) were used for the synthesis procedure such as two components of epoxy-hardener, plant/ drying oil and hybrid composite as displayed in Figure 7.

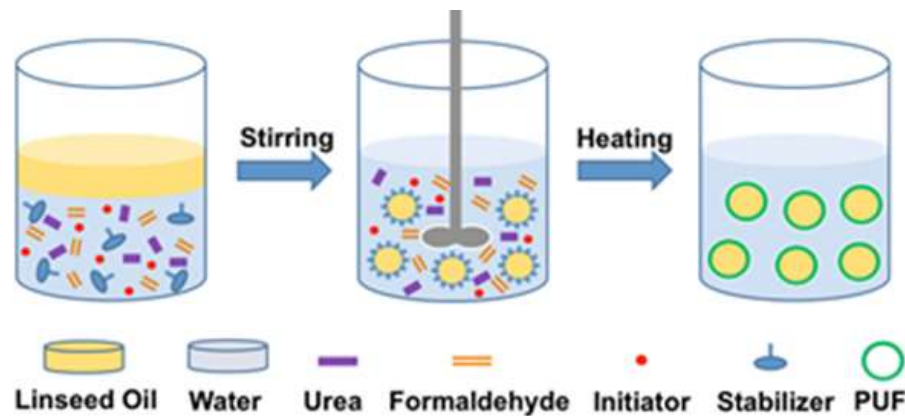


Figure 7 The scheme of the synthesis procedure of PUF microcapsules containing linseed oil [53].

Among the factors affecting shell wall thickness and mechanical strength are low initial pH, smaller amount of DCPD added, contaminated glassware, unbalanced mixer as enumerated by Brown et al. [40]. Study by Sinou Lang et al. [32] indicated that increasing stir rate could provide a stronger shear force applied, which leads to thinner shell of the microcapsules. He also mentioned the effect of temperature during synthesis at higher temperature showed improved shell strength and higher surface roughness [32].

The healing agents are usually made from reactive chemical and liquid phase because of free flow through the crack/ damage region. The previous study showed lots of materials were encapsulated as the core material or healing agent, such as linseed oil [4, 27, 31-36], tung oil [28, -30], others drying oil [10, 25, 26], two-component epoxy hardeners [5, 6, 9, 12, 14, 20, 22, 49], silyl ester [8, 15, 36], hydrolysable organic silane [141], antibacterial polymer [145, 173], hybrid nanocomposite [16], dicyclopentadiene (DCPD) [2, 21, 44], diisocyanate (HDMI) [14], TiO₂ [9], isocyanate (IPDI) [18] and chitosan [45, 46] which released the agent when damage occurred. Among the core or healing agents' material displayed, the group of drying oil and epoxy components are the most common and popular for self-healing coating study. Table 3 present a summary comparison of the encapsulation technique and optimum wt. % of microcapsule by other researchers. However, the high environmental toxicity of the coatings of some of the chemical agents has restricted their application in many parts of the World due to their effect on human life [30]. Drying oil is a kind of environmentally friendly corrosion-protective agent [25-36].

Table 3 Comparison of the encapsulation method, final diameter of capsule and the optimum wt. % of microcapsule incorporated with coating matrix.

Author/ year	Synthesis method	Shell material	Core material	Diameter size	Optimum wt. % of microcapsule in coating.
Blaiszik <i>et al.</i> [20] (2009)	In situ polymerization	Poly-urea-formaldehyde (PUF)	DCPD	300nm-300µm	-
Garcia <i>et al.</i> [14] (2011)	In situ polymerization	Poly-urea-formaldehyde (PUF)	Silyl ester	50-100µm	-
Yabuki <i>et al.</i> [8] -2012		-	Superabsorbent and vinyl-ester polymer	15µm	5 – 10 wt.%
Liao <i>et al.</i> [5] (2012)	In situ polymerization	Poly-urea-formaldehyde (PUF)	Linseed oil	80µm	5 wt.%
Zhao Yang <i>et al.</i> [52] (2012)	In situ polymerization	Poly-urea-formaldehyde (PUF)	Epoxy 501 and E-51	100µm	10 wt.%
Xiuxiu <i>et al.</i> [14] (2012)	Interfacial polymerization	EDA	Epoxy resin	100µm	20 wt.%
Haiyan <i>et al.</i> [29] (2017)	Solvent evaporation method	Polysulfone (PSF)	Tung oil	130 and 9 µm	10 wt.%
Suwadee <i>et al.</i> [16] (2017)	In situ polymerization	Poly-urea-formaldehyde (PUF)	Modified silica nanoparticle	50-100µm	10 wt.%

The rough morphology surface of the capsules ensures their good mechanical bonding to coating matrix. Their spherical shape (micro/nano scale) guarantees the storage role of capsules and easy dispersion into the coating before applying as shown in Figure 8 [20, 30, 33, 34, 51].

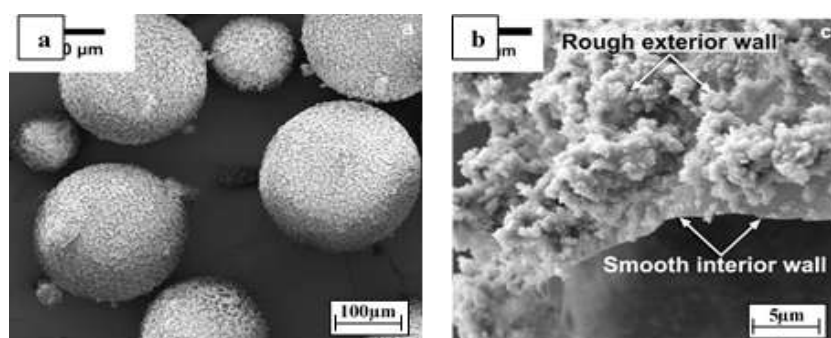


Figure 8. SEM images of Epon 828–EPA microcapsules showing (a) the spherical capsules produced, and (b) a view of the interior of a ruptured microcapsule showing the smooth interior wall and the rough exterior of the wall [20].

Effect of Particle Size and Reagents Loading on Self-Healing Performance

The ultimate aim of the microcapsules incorporation is to deliver a sufficient quantity of the healing agent to cover the damage. From the theoretical and logical view, the optimum loading of healing agent needed to fill the crack can be found by multiplying the volume of the damage by healing agent [21]. Table 4 presented the relationship between mean diameters of synthesized microcapsules versus agitation rate in encapsulation process. There are two ways and strategies to deliver this correct amount of healing agent which is through high microcapsule loading or by using bigger microcapsule size. A fair advantage of the former approach was pointed out by A. Kumar *et al.* [7] who wrote that the larger microcapsules could contain and deliver more healant once

they had been ruptured. Kumar et al. also noted that probability of rupture of the smaller number of large microcapsules was higher than rupture of a larger number of small microcapsules capable to deliver the same amount of healing agent and suggested to use capsules 63 – 150 μm in diameter. Results of Rule et al. [21] have also demonstrated superior performance of larger microcapsules at a given weight fraction. For instance, as it was shown by E. Brown et al. [40], the maximum healing efficiency for 180 μm microcapsules occurs near 5wt. %, whereas for 50 μm the high healing efficiency reached only at 20wt. % capsule loading level. Brown et al. also concluded that the microcapsule loading at which this maximum occurs depends on microcapsule diameters [40].

Table 4 Comparison the different encapsulation material (shell and core) and the size depending on the agitation rate.

Author	Shell material	Healing agent	Diameter	Shell wall thickness	Agitation speed (rpm)
Brown <i>et al.</i> [44]	PUF	DCPD	10-1000 μm	160-220nm	200-2000
Blaiszik <i>et al.</i> [20]	PUF	Epon 828 and EPA	300nm-300 μm	160nm	800
Suryanarayana, Hatami <i>et al.</i> [33, 34]	PUF	Linseed oil	50 μm	200nm	250
Barbara <i>et al.</i> [18]	PU/ PUF	IPDI	75.8 μm	2.2 μm	500
Samad Zadeh <i>et al.</i> [30]	PUF	Tung oil	40 - 100 μm	-	200-400
Dawei Sun <i>et al.</i> [14]	Double shell TEPA/ PUF particle	HMDI	74.2 $\pm$ 14.0 μm	1.52 $\pm$ 0.21 μm	850
Zhao Yang <i>et al.</i> [51]	PUF	Epoxy BGE and E-51	25- 250 μm	-	900
Suwadee <i>et al.</i> [36]	PUF	Linseed oil	10 μm	-	2000

Blaiszik et al. [20] made it possible to start healing process at such a small scale which could not be reached earlier-they produced UF-shell capsules with mean diameters as small as 220 nm and as large as 1.65 μm utilized sonication technique. The capsules exhibited good thermal stability, did not cause any significant reduction in elastic modulus, and significantly increased fracture toughness of the composite. Dawei Sun et al. [14] indicated that the final size of microcapsules strongly affects the self-healing performance and it is controllable by adjusting the agitation rate during synthesis process. It was also concluded that the higher agitation rate produced smaller microcapsules yielded from smaller oil droplets due to the stronger shear force [15] as shown in Figure 9 (a). Figure 9 (b) displayed the microcapsules mostly transparent spherical particles (dying oil) with shiny liquid core material when observed using the optical microscope [32].

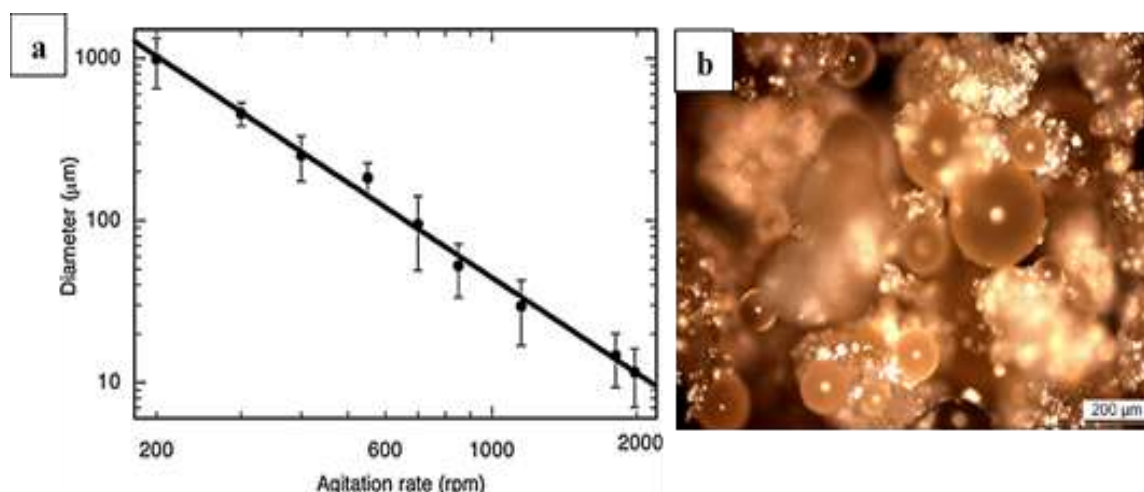


Figure 9 (a) Mean diameter of synthesized microcapsules vs. agitation rate in encapsulation process [167,128] and (b) Microcapsule [129].

The thick layer of the outer surface (shell) is greatly impacted by the reaction parameters such as concentration of wall material, initial pH value, surfactant, and stirring rate [50]. Selection of higher stirring rate helped to prepare a smoother microcapsule to avoid the deposition rate of UF nanoparticles due to the high shear rate of the solution during synthesis. On the other hand, a higher stirring rate can reduce the aggregates of UF nanoparticles that help to form smooth surface [50]. Types of agitator used also influence the microcapsule size together with agitation speed such as half-moon impeller [32], 4-bladed metal propeller [4], 6-bladed metal propeller [17] and 3-bladed metal propeller [14, 27]. During the synthesis process, the fluid flow around the propeller is turbulent, many larger micro-eddies exist when the flow is away from the propeller. In the vicinity of the propeller blades, many smaller micro-eddies exist, producing a wider length scale [52]. Tatyana et al. [4] mentioned that the influence of 4-bladed metal propeller agitation rate on size of microcapsules is significantly smaller because of the size of emulsion droplets. It should be noted that the maximum microcapsules loading was effected by the mechanical properties of the coating such as adhesion and tensile test. In self-healing coatings, maintaining the mechanical properties should be considered in achieving a high healing performance [35].

Plant Oil or Drying Oil Properties

Most commonly, the drying oils or vegetable oils have chemical compositions of water-insoluble, unsaturated glycerides of long chain fatty acids. Most of these oils contain less than 10% of any particular saturated fatty acid residue. The degree of double bond unsaturation controls the drying rate; the higher degree of unsaturation or iodine number, the faster the drying or polymerization of the oil, which is the aim of healing performance [31]. Drying oils harden to a tough, solid film after a period of exposure to air (oxygen) through autoxidation instead of evaporation of water or other solvents [29]. Previous researchers have examined the use of alternative healing agents including the drying oil that has been used and successful synthesis of healing agents such as linseed oil [4, 27, 31-36], tung oil [28-30], chia oil [25], lemon oil [26], and oregano oil [46]. For that reason drying oils are particularly promising as healing agent since they are low cost and environmentally friendly, and are already used in the paint and coating industry [31].

Linseed Oil as Healing Agent

Linseed oil (LO) is obtained from flaxseed oil or flax oil through solvent extraction or pressing, is a colourless to yellowish oil obtained from the dried, ripened seeds of the flax plant (*Linum usitatissimum*) as shown in Figure 10. It is one of the most useful natural oils in the industry. Linseed oil has some similar properties of Tung oil and the word “*Usitatissimum*” means “most useful” [17]. It is used as a preservative for wood, concrete structure, an ingredient in paints and waterproof coating, varnishes, also as a component of caulk and mortar [30]. Linseed oil is common and popular drying oil because of the ability to dry quickly and polymerize into a

glossy, tough, waterproof coating that is especially valuable in varnishes, paints, linoleum, oil cloth and printing inks. Pure linseed oil was resistant to water and alkali solution [30].

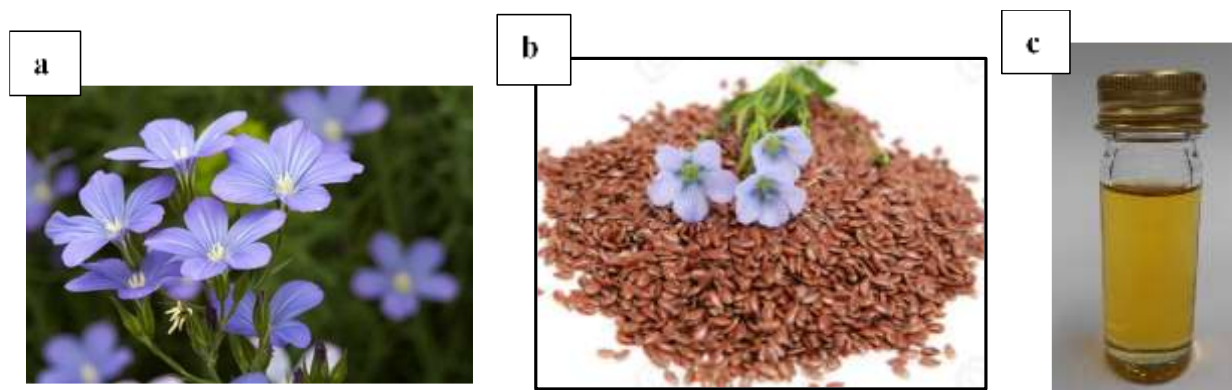


Figure 10 (a) Flax flowers, (b) flax seeds and (c) yellowish colour of commercial linseed oil

Chemically, the polyunsaturated fatty acids from the LO readily oxidize to form a three-dimensional network that protects the metal from corrosive behaviour. This high degree of unsaturation gives these macromolecules potential for functionalization and subsequent polymerization to form a highly cross-linked polymer matrix or other chemical. The bonding also gives flexibility to the surface, making it capable of withstanding wear and tear [30]. Thus, microcapsules containing LO are attractive for the preparation of anticorrosive paints and coatings [17, 30].

Linseed oil is broadly used and applied as coating protection in oil and gas industry, and has been investigated with different formulation and secret recipe in the recent years. Suryanarayana et al. [33] in 2008 investigated how the cracks in a coating (paint) were successfully healed when linseed oil was released from ruptured microcapsules. The corrosion resistance and adhesion strength, nanocapsule incorporated coating with optimum capsule was studied by Hatami Boura et al. [34] in 2012. Furthermore in 2014, Behzadnasab et al. [35] presented that epoxy coating with different size of microcapsule enhanced the mechanical properties and healing performance. Due to the increasing of technology and demand, in 2015 the mixture of LO microcapsule with octadecylamine (ODA) as corrosion and Co-octoate as drier material were introduced by Tamas Szabo et al. [36]. One year later, María de la Paz Miguel et al. [27] produced a strong enough capsule by one acid stage method. With the latest smart coating and technology, Behzadnasab et al. [31] in 2017 continued the study with new formulation through the various sizes of microcapsule prepared for a long term corrosion performance, which was confirmed with EIS test. Sinuo Lang et al. [32] studied the effects of parameters such as molecular weight of poly (vinyl alcohol) (PVA) stabilizers, stir rates, and the reaction temperatures on the microcapsule properties. From 2008 onward, study of the evolution of PUF encapsulated microcapsule incorporated with epoxy coating or paint in latest technology and advanced system has increased [27, 30-36].

Epoxy Coating

Epoxy matrix or paint is widely used in the heavy duty anticorrosion coatings in oil and gas industry due to its exceptional excellent properties, such as easy processing, excellent solvent and chemical resistance, high safety, toughness, low shrinkage on cure, mechanical and corrosion resistance with excellent adhesion to many metal substrates [44]. In different situations and applications, the structures of epoxy become primer coating and a polyurethane as topcoat. Epoxy matrix also has some inferior characteristics, such as high rigidity, poor impact strength, and moisture absorbance [44]. To overcome and improve the properties such as anticorrosion and antibacterial performance, mixture with binder/ pigment and inhibitor such as chitosan [40, 45], polyaniline and polypyrrole [42, 44], ultra-short fiber [45], are added to epoxy paint. Therefore, epoxy matrix or paint is a good candidate of healing agent or coating matrix for the fabrication of self-healing coating [14].

Epoxy Containing Self-Healing Systems

In many cases and situations, the epoxy paints are used for the protection in marine environment and corrosive atmospheres. The coating film undergoes the changes in surface morphology, leading to the formation of micro-

cracks which subsequently propagate and expose substrate to sea water penetration, atmospheric moisture and oxygen [17]. When an epoxy composite or coating needs to be protected from micro cracking, it seems to be a better way to also do that using epoxy. The literature survey shows that performed investigations on the epoxy monomers could be efficiently employed both as core material and as a matrix. A high compatibility of epoxy material with the matrix is a main advantage possessed by such systems and resulting in good adhesion of the newly formed film with the matrix or of the capsule shell with the matrix if epoxy is used as an encapsulation agent [49]. In both cases, the improved repair effect can be expected [49].

The development of self-healing coatings with microencapsulated epoxy as microcapsule/ coating matrix or other capsule chemical/ coating matrix has also increased dramatically. Many researchers demonstrated the effectiveness of both model for industrial coating system such as epoxy-amine paint (eurokote 450) [3], epikote 828 and gaskamine 240 (2:1) [4], butylglycidylether (BGE) and E-51 [5], bisphenol A and triethylenetetramine [12], epolam 5015 and hardener [14, 15], diglycidyl ether of bisphenol-A (EDGBA) and inxylene/butanol (7:3) [16], epoxy 501 and E-51 [17], epikote 828 and epikure F205 [18], epoxy BGE and E-501 [19], epon 828 and diethylenetriamine (DETA) [2, 20, 21], PDMS fiber and DBTL catalyst [19].

Li Yuan et al. [49] demonstrated the DGEBA with BGE. The result showed the diluent decreases the viscosity of the epoxy and allows healing agent to release readily from the capsule through the capillary effect when its rupture occurs. The ability of micro/ nanocapsules of linseed oil in epoxy paint films to release healing material, which heals crack efficiently with satisfactory protective properties, was confirmed through corrosion test done by Kouhi et al. [50]. Another approach to the use of epoxy as a healing agent and coating matrix are Zhao Yang et al. [52] showed that the epoxy resin is released to heal the crack damaged and the rough microcapsule appearance has provided good anchoring between microcapsule and paint matrix.

The homogeneous capsule dispersion in epoxy matrix or paint was highly dependent on the capsule characteristics such as capsule size, capsule drying time, epoxy mixing time, mixing rate of the capsule in coating matrix, separation method and various capsule preparation parameters [50]. Sinou Lang et al. [32] demonstrated that if the combination of more than one capsule or inhibitor to be incorporated with epoxy matrix result in relatively very high viscosity, at the same time, microcapsules could be agglomerated, poked

and broken easily during the mixing process. Thus, solvents like acetone or any chemical are required to dilute the epoxy coating and to reduce the shear force applied to the microcapsules during mixing operations. The FESEM image in Figure 11 displayed the cross section of microcapsule coating distribution without breakage during the mixing, which further ensures the self-healing performance of the coating [32].

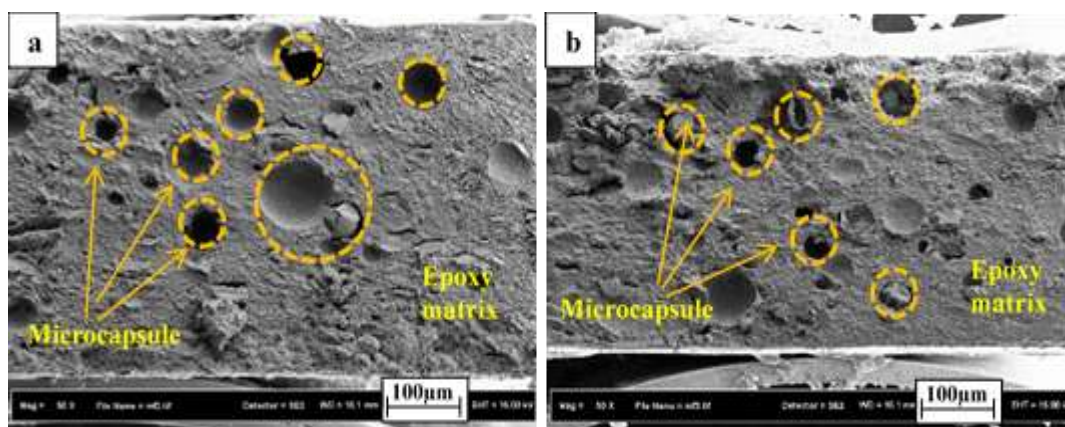


Figure 11 (a) and (b) FESEM image for cross-section of the self-healing coating film.

Suryanarayana et al. [33] studied on the mixing microcapsule under slow agitation of 200 rpm to epoxy resin matrix at ambient temperature to inhibit capsule rupture during mixing for 15 min and to ensure that the capsules did not agglomerate was successful. Therefore, they were uniformly dispersed throughout the self-healing coating. The dry or final self-healing coating was dependent on the capsule size, addition of inhibitor/ binder and

epoxy matrix and hardener content for specific application such as antibacterial and anticorrosion performance. Variable of thickness such as 150 μ m [15, 20, 33, 34], 120 μ m [5, 32], 200 μ m [29, 52], 240 μ m [14] and 420 μ m [31] were achieved from the previous study of this area. The methods used to apply the coating on the substrate contributes to the final thickness by many researchers, indicate spin coating [8], spray [5], bistoury blade or doctor blade [52], and brushed [14]. The best method to apply the self-healing coating by brushing due to high viscosity formulation to reduce the rupture of microcapsule and to make the distribution uniform. The correlation of rough outer surface enhanced adhesion and promoting bonding of the microcapsules to the polymer matrix was widely known [50]. Hence, it increased the probability of capsule fracture, which increased healing agent delivery, and consequently improved self-healing performance [20].

The addition of inhibiting agents to coatings effectively facilitated and increased the self-healing capability. The addition of a corrosion inhibitor to store and release the inhibitor would be useful for achieving smart and advanced long-term protection by self-healing coating against corrosion with specific application such as antibacterial properties.

CONCLUSION

Self-healing coating involved the kindness of large troops of researchers to create the optimum formulation for corrosion protection of metal substrates especial for steel material. The main corrosion issue indicators is also costs associated with repairment/replacement of metal substrates or structure. Linseed oil are natural solutions that can polymerize in a short period, allowing self-healing of a coating and delivering efficient corrosion protection. Linseed oils were efficiently encapsulated as a core material (healing agent) with the most commonly urea-formaldehyde (UF) shell. In situ polymerization process is the most common method for self-healing microcapsules. Its compensation include simple operation, controllable capsule size and shell thickness, low cost, and suitability for upscale industrial production. The overall process parameters influencing the final size of micro-/nano-capsules containing linseed oils are agitation rate, stirrer geometry, stabilizer (type and amount), and temperature setting.

Moreover, with increased exposure time to the salt solution, the corrosion behavior of scratched coated samples shifted from universal corrosion to crevice corrosion. Our results show that linseed oil alone was only partly successful as a healing agent. To improve the anti-corrosion performance of this method the addition of corrosion inhibitors to microcapsules is recommended. Many research efforts were put to identify the corrosion behavior using immersion test, tafel polarization curve, and electrochemical impedance spectroscopy (EIS) method. The improvement in the corrosion protection was due to the presence of blistering bubbles, which were talented to cause the receptive stimulus required to release the core material existing in the microcapsules. The replacement of common coatings with self-healing ones can increase reliability, consistency, and safety, cost savings, and material conservation, producing engineers closer to better and more exact life estimations. The biggest challenge for end-user industries is to choose anti-corrosion coatings with a low impact on the any environment especially in marine environment. Thus, the natural dry oils as core materials and the request for waterborne anti-corrosion coatings will rise considerably during the forecast phase.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the Fundamental Research Grant Scheme (FRGS-EC) FRGS-EC/1/2024/TK09/UTEM/02/4 and FRGS-EC/1/2024/FTKIP/F00601, the Universiti Teknikal Malaysia Melaka (UTeM), Malaysia, the Faculty of Mechanical Engineering, Department of Bioscience, Faculty of Science UTM, and UTeM for research facilities, as well as the Ministry of Higher Education's (MOHE) SLAB/SLAI schemes and the FTKIP 2025 Final Year Project Budget.

REFERENCES

1. Jiang, J., Fu, Y., Zhang, Q., Zhan, X., Chen, F. Novel Amphiphilic Poly (Dimethylsiloxane) based Polyurethane Networks Tethered with Carboxybetaine and their Combined Antibacterial and Anti-adhesive Property. *Appl. Surf. Sci.*, 412, (2017) pp. 1–9.
2. White S.R., Sottos N.R. Guubelle P.H, Moore J.S. Autonomic Healing of Polymer Composites. *Letter to Nature*, 409, (2001) pp. 794-817.

3. Nesterova, T., Dam-johansen, K., Kiil, S., Synthesis of Durable Microcapsules for Self-healing Anticorrosive Coatings : A comparison of Selected Methods. *Prog. in Org. Coatings*, 70, (2011) pp. 342–352.
4. Nesterova, T., Dam-johansen, K., Thorslund, L., Kiil, S., Microcapsule-Based Self-healing Anticorrosive Coatings : Capsule Size, Coating Formulation, and Exposure Testing. *Prog. in Org. Coatings*, 75, (2012) pp. 309–318.
5. Liao, L.P., Zhang, W., Zhao, Y., Liao, L.P. Preparation and Healing Property Evaluation of Self-repairing Polymer Coating. *Surface Eng.*, 30(2), (2016) pp. 138-141.
6. Mehta, N.K., Bogere, M.N. Environmental Studies of Smart/ Self-healing Coating System for Steel. *Prog. in Org. Coatings*, 64, (2009) pp. 419–428.
7. Kumar, A., Stephenson, L.D., Murray, J.N., Self-healing Coatings for Steel. *Prog. in Org. Coatings*, 55, (2006) pp. 244–253.
8. Yabuki, A., Okumura, K. Self-healing Coatings using Superabsorbent Polymers for Corrosion Inhibition in Carbon Steel. *Corros. Sci.*, 59, (2012) pp. 258–262.
9. Yabuki, A., Sakai, M. Self-healing Coatings of Inorganic Particles using a pH-Sensitive Organic Agent. *Corros. Sci.*, 53, (2011) pp. 829–833.
10. Szabó, T., Molnár-nagy, L., Bognár, J., Nyikos, L., Telegdi, J. Self-healing Microcapsules and Slow Release Microspheres in Paints. *Prog. in Org. Coatings*, 72, (2011) pp. 52–57.
11. Bekas, D.G., Tsirka, K., Baltzis, D., Paipetis, A.S. Self-healing Materials : A Review of Advances in Materials, Evaluation, Characterization and Monitoring Techniques. *Compos. Part B*, 87, (2016) pp. 92–119.
12. Islam, N., Halder, S., Goyat, M.S., Effect of Epoxy Resin and Hardener Containing Microcapsules on Healing Efficiency of Epoxy Adhesive based Metal Joints. *Mater. Chem. and Phys.*, 171, (2016) pp. 267–275.
13. Sun, D., Zhang, H., Tang, X., Yang, J. Water Resistant Reactive Microcapsules for Self-healing Coatings in Harsh Environments. *Polymer*, 91, (2016) pp. 33–40.
14. Inime I. U., Hongwei S., Enobong F. D., Jianyang L., Songhua G., Fuchun L., En-Hou H. Review: Active anticorrosion and self-healing coatings: A review with focus on multi-action smart coating strategies. *Journal of Materials Science & Technology* 116 (2022) pp. 224–237.
15. Natasa Z. T.,1, Abdullah N. M., Maitha A., Nujood A., Ana A. Review: Advanced application of drying oils in smart self-healing coatings for corrosion protection: Feasibility for industrial application *Progress in Organic Coatings* 172 (2022) pp. 107070
16. Park, S., Shin, Y., Lee, J., Preparation and Characterization of Microcapsules Containing Lemon Oil. *J. of Colloid & Inter. Surface*, 241, (2016) pp. 502–508.
17. De, M., Miguel, P., Ollier, R., Alvarez, V., Vallo, C., Effect of the Preparation Method on the Structure of Linseed Oil-Filled Poly (Urea-Formaldehyde) Microcapsules. *Prog. in Org. Coatings*, 97, (2016) pp. 194–202.
18. Credico, B. Di, Levi, M., Turri, S. An Efficient Method for the Output of New Self-Repairing Materials through a Reactive Isocyanate Encapsulation. *Eur. Polym. J.*, (2013) pp. 15–17.
19. Yang Z., Wei Z., Le-Ping W. The Self-healing Composite Anticorrosion Coating. *Physics proceedia*, 18, (2011) pp. 216-221.
20. Blaiszik, B.J., Caruso, M.M., Mcilroy, D.A., Moore, J.S. Microcapsules Filled with Reactive Solutions for Self-healing Materials. *Polymer*, 50, (2009) pp. 990–997.
21. Rule, J.D., Sottos, N.R., White, S.R. Effect of Microcapsule Size on the Performance of Self-healing Polymers. *Polymers*, 48, (2007) pp. 3520–3529.
22. Doan, T.Q., Leslie, L.S., Yup, S., Bhargava, R. Characterization of Core-Shell Microstructure and Self-healing Performance of Electrospun Fiber Coatings. *Polymer*, 107, (2016) pp. 263–272.
23. Chaudhari, A., Gite, V., Rajput, S., Mahulikar, P., Kulkarni, R., Development of Eco-friendly Polyurethane Coatings based on Neem oil Polyetheramide Neem oil. *Ind. Crop. and Prod.*, 50, (2013) pp. 550–556.
24. Alves, G., Azeredo, D., Lúcia, T., Stamford, M. Combined Application of Essential Oils from *Origanum Vulgare* L. and *Rosmarinus officinalis* L. to Inhibit Bacteria and Autochthonous Micro Flora Associated with Minimally Processed Vegetables. *Food Research Inter.*, 44, (2011) pp. 1541–1548.

25. Ixtaina, V.Y., Julio, L.M., Wagner, J.R., No-, S.M., Tom, M.C., Physicochemical Characterization and Stability of Chia Oil Microencapsulated with Sodium Caseinate and Lactose by Spray-Drying. Powder Technol. (2014)
26. Park, S., Shin, Y., Lee, J., Preparation and Characterization of Microcapsules Containing Lemon Oil. J. of Colloid & Inter. Surface, 241, (2001) pp. 502–508.
27. De, M., Miguel, P., Ollier, R., Alvarez, V., Vallo, C., Effect of the Preparation Method on the Structure of Linseed Oil-Filled Poly (Urea-Formaldehyde) Microcapsules. Prog. in Org. Coatings, 97, (2016) pp. 194–202.
28. Yang, X., Zhang, S., Li, W. The Performance of Biodegradable Tung Oil Coatings. Prog. in Org. Coatings, 85, (2015) pp. 216–220.
29. Li, H., Cui, Y., Wang, H., Zhu, Y., Wang, B., Preparation and Application of Polysulfone Microcapsules Containing Tung Oil in Self-healing and Self-Lubricating Epoxy Coating. Colloids & Surfaces A Physicochem. Eng. Asp., 518, (2017) pp. 181–187.
30. Samadzadeh, M., Boura, S.H., Peikari, M., Ashrafi, A., Kasiriha, M., Tung oil : An Autonomous Repairing Agent for Self-healing Epoxy Coatings. Prog. in Org. Coatings, 70, (2011) pp. 383–387.
31. Behzadnasab, M., Mirabedini, S.M., Esfandeh, M., Farnood, R.R. Evaluation of Corrosion Performance of a Self-healing Epoxy-Based Coating Containing Linseed Oil-Filled Microcapsules via Electrochemical Impedance Spectroscopy. Prog. in Org. Coatings, 105, (2017) pp. 212–224.
32. Lang, S., Zhou, Q. Synthesis and Characterization of Poly (urea-formaldehyde) Microcapsules Containing Linseed Oil for Self-Healing Coating Development. Prog. in Org. Coatings, 105, (2017) pp. 99–110.
33. Suryanarayana, C., Rao, K.C., Kumar, D., Preparation and Characterization of Microcapsules Containing Linseed Oil and its use in Self-healing Coatings. Prog. in Org. Coatings 63, (2008) pp. 72–78.
34. Boura, S.H., Peikari, M., Ashrafi, A., Samadzadeh, M., Self-healing Ability and Adhesion Strength of Capsule Embedded Coatings - Micro and nano Sized Capsules Containing Linseed Oil. Prog. in Org. Coatings, 75, (2012) pp. 292–300.
35. Behzadnasab, M., Esfandeh, M., Mirabedini, S.M., Zohuriaan-mehr, M.J., A : Preparation and Characterization of Linseed Oil-Filled Urea – Formaldehyde Microcapsules and their Effect on Mechanical Properties of an Epoxy-Based Coating. Colloids & Surfaces A Physicochem. Eng. Asp., 457, (2014) pp. 16–26.
36. Szabó, T., Telegdi, J., Nyikos, L. Linseed Oil-Filled Microcapsules Containing Drier and Corrosion Inhibitor – their Effects on Self-Healing Capability of Paints. Prog. in Org. Coatings, 84, (2015) pp. 136–142.
37. Prawoto, Y., Synergy of Erosion and Galvanic Effects of Dissimilar Steel Welding : Field Failure Analysis Case Study and Laboratory Test Results. J. King Saud Univ. - Eng. Sci., 25, (2013), pp. 59–64.
38. Telegdi, J., Otmacic-Curkovic, H., Marusic, K., Al-Taher, F., Stupnisek-Lisac, E., K'alm'an, E. Inhibition of Copper Corrosion by Self-Assembled Amphiphiles. Chem. Biochem. Eng. Q., 21(1), (2007) pp. 77–82.
39. García, S.J., Fischer, H.R., Zwaag, S. Van Der. A Critical Appraisal of the Potential of Self-healing Polymeric Coatings: Review. Prog. in Org. Coatings, 72, (2011), pp. 211–221.
40. N. Brown, M.R. Kessler, N.R. Sottos, S.R. White. In Situ Poly(Urea Formaldehyde) Microencapsulation of Dicyclopentadiene. J. Microencapsul. 20(6) (2003) pp. 719–730.
41. Yu, D., Zhi, M., Qiu, M. Self-Healing Polymeric Materials Based on Microencapsulated Healing Agents : from Design to Preparation. Prog. Polym. Sci., 49–50, (2015) pp. 175–220.
42. Zuev, V. V, Lee, J., Kostromin, S. V, Bronnikov, S. V, Bhattacharyya, D. Statistical Analysis of the Self-Healing Epoxy-Loaded Microcapsules Across their Synthesis. Mater. Lett., 94, (2013) pp. 79–82.
43. Soo, B., Cho, H., White, S.R., Braun, P. V. Self-Healing Polymer Coatings. Advanced Material., 21, (2009) pp. 645–649.
44. Huang, M., Yang, J. Salt Spray and EIS Studies on HDI Microcapsule-Based Self-Healing Anticorrosive Coatings. Prog. in Org. Coatings, 77, (2014) pp. 168–175.
45. Chem, J.M., Zheludkevich, M.L., Tedim, J., Freire, C.S.R. Self-Healing Protective Coatings with “Green” Chitosan based Pre-Layer. J. of Mater. Chems., 21, (2011) pp. 4805–4812.

46. Fakhreddin, S., Zandi, M., Rezaei, M., Farahmandghavi, F. Two-Step Method for Encapsulation of Oregano Essential Oil in Chitosan Nanoparticles : Preparation, Characterization and in Vitro Release Study. *Carbohydr. Polym.* 2013, 95, (2013) pp. 50–56.
47. Samadzadeh, M., Boura, S.H., Peikari, M., Kasiriha, S.M., Ashrafi, A., A review on Self-healing Coatings based on Micro/ Nanocapsules. *Prog. in Org. Coatings*, 68, (2010) pp. 159–164.
48. Gonzalez, S., Kittel, J., Self-healing coatings : An Alternative Route for Anticorrosion Protection. *Prog. in Org. Coatings*, 63, (2008) pp. 307–315.
49. Yuan, L., Liang, G., Xie, J., Li, L., Guo, J. Preparation and Characterization of Poly (Urea-Formaldehyde) Microcapsules Filled with Epoxy Resins. *Polymers*, 47, (2006) pp. 5338–5349.
50. Kouhi, M., Mohebbi, A., Mirzaei, M., Peikari, M., Optimization of Smart Self-healing Coatings based on Micro/ Nanocapsules in Heavy Metals Emission Inhibition. *Prog. in Org. Coatings* 2013.
51. Yang Z., Wei Z., Le-Ping W. The Self-healing Composite Anticorrosion Coating. *Physics proceedia*, 18, (2011) pp. 216-221.
52. Yang, Z., Wei, Z., Le-ping, L., Si-jie, W., Wu-jun, L., Self-healing Coatings Containing Microcapsule. *Appl. Surf. Sci.*, 258, (2012) pp. 1915–1918.
53. Yu, D., Zhi, M., Qiu, M. Self-Healing Polymeric Materials Based on Microencapsulated Healing Agents : from Design to Preparation. *Prog. Polym. Sci.*, 49–50, (2015) pp. 175–220.