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Optimization and Evaluation of Autonomous Self-Healing Carbon Fiber Reinforced Polymer Composites with Embedded Microcapsules for Aircraft Skin Damage Repair

Usman, Y & Alonge, T. T.
Aviation Management School
Nigerian College of Aviation Technology
Zaria, Nigeria
Authors E-mails: usmanyaks@gmail.com, oluwatomilayo90@gmail.com
Phone Nos: +2348036638047, +2347063461967

ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites are widely used in aircraft skins but are susceptible to barely visible impact damage that compromises residual strength. This study evaluates an autonomous self-healing CFRP system incorporating urea-formaldehyde microcapsules containing diglycidyl ether of bisphenol-A (DGEBA) epoxy healing agent. Microcapsules were synthesized via in-situ polymerization and optimized using a central-composite response-surface design examining core-to-shell ratio, agitation rate, and reaction temperature. Optimal conditions (2:1 ratio, 700 rpm, 60 °C) yielded capsules of 105 ± 8 μm mean diameter with 71.6 ± 0.5% core content and thermal onset of 261 °C. Capsules were dispersed at 0–10 wt% into aerospace epoxy and fabricated into quasi-isotropic laminates by vacuum-assisted resin infusion. Processability was retained with void content below 3%. At 5 wt% loading, tensile and flexural strengths decreased by approximately 9% and 10%, respectively. Self-healing efficiency after matrix cracking reached 68.4 ± 4.2% at room temperature and 74.1 ± 3.8% at 50 °C, while delamination recovery was 54.7–61.3%. The results demonstrate that optimized microcapsule systems can provide meaningful autonomous healing in aerospace-grade CFRP while maintaining acceptable structural performance.

Keywords: Self-healing composites; Microcapsules; CFRP; Aircraft skin; Urea-formaldehyde; Agitation Damage repair

1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) composites have become the material of choice for modern aircraft primary structures, including fuselage and wing skins, due to their exceptional specific strength, stiffness, fatigue resistance, and corrosion immunity compared with traditional aluminum alloys (Soutis, 2005). Commercial aircraft such as the Boeing 787 and Airbus A350 incorporate more than 50% by weight of CFRP, resulting in significant reductions in structural weight and fuel consumption.

Despite these advantages, CFRP laminates are susceptible to barely visible impact damage (BVID) caused by tool drops, hail, bird strikes, or ground handling incidents. Such damage often manifests as matrix microcracking, fiber-matrix debonding, and interlaminar delamination that can propagate under cyclic loading and compromise residual strength (Abrate, 1998; Richardson & Wisheart, 1996). Because damage is frequently internal and not readily detectable by visual inspection, extensive non-destructive evaluation campaigns and conservative design allowables are required, increasing maintenance costs and downtime (Cantwell & Morton, 1991). Aircraft skin structures fabricated from conventional CFRP require frequent inspection and manual repair when micro-damage accumulates. Scarf or stepped bonded repairs are labor-intensive, require controlled environments, and can introduce residual stresses or weight penalties (Baker et al., 2004). Moreover, undetected BVID can lead to progressive delamination growth and premature failure. While microcapsule-based self-healing has demonstrated healing efficiencies of 50–75% in laboratory epoxy and glass-fiber systems, its translation to high-performance unidirectional or woven CFRP intended for primary aircraft skins remains limited. Critical issues include the trade-off between healing efficiency and initial mechanical properties, the influence of capsule size and concentration on processability and fiber volume fraction, thermal stability under aerospace service temperatures, and reliable healing under realistic damage modes (matrix cracking and delamination).

Autonomous self-healing strategies offer a promising route to mitigate these limitations. Inspired by biological systems, extrinsic self-healing approaches embed discrete containers of healing agents that rupture upon crack propagation, releasing reactive monomers that polymerize and restore mechanical integrity (White et al., 2001). Microcapsule-based systems have received particular attention for aerospace applications because they can be dispersed within the matrix or interleave regions without major changes to existing composite manufacturing processes (Pittala et al., 2022).
The aim of this study is to evaluate an autonomous self-healing CFRP with embedded microcapsules for enhanced damage repair in aircraft skin structures. The specific objectives addressed in this paper are to: (1) synthesize microcapsules containing epoxy resin healing agents and optimize their shell ratio, agitation rate, and reaction temperature; (2) fabricate CFRP composite specimens embedded with self-healing microcapsules suitable for aircraft skin applications; (3) characterize the mechanical, thermal, and structural properties of the developed self-healing CFRP composite, including tensile strength, impact resistance, and thermal stability; and (4) evaluate the self-healing efficiency of the embedded microcapsules under controlled damage scenarios such as micro-cracks and delamination.

2. LITERATURE REVIEW

CFRP laminates derive their outstanding in-plane properties from high-modulus carbon fibers (typically 230–300 GPa) embedded in a thermosetting epoxy matrix. Fiber volume fractions of 55–65% are standard for aircraft skins, delivering specific moduli and strengths that far exceed aluminum alloys (Soutis, 2005). Manufacturing processes such as autoclave curing of prepregs and out-of-autoclave vacuum infusion have matured to the point that large, integrated structures can be produced with low void content. However, impact events of only a few joules can produce extensive internal delamination while leaving the outer surface essentially unmarked—a phenomenon known as barely visible impact damage (BVID). Subsequent compressive loading can trigger delamination buckling and rapid strength reduction (Abrate, 1998). Current airworthiness regulations therefore mandate large knockdown factors and periodic ultrasonic or thermographic inspections. Bonded scarf repairs restore strength efficiently but are time-consuming and sensitive to surface preparation and curing conditions (Baker et al., 2004).

Self-healing composites are designed to autonomously repair damage through intrinsic or extrinsic healing strategies, inspired by biological systems (Zhang et al., 2021). Intrinsic self-healing involves reversible chemistries within the polymer matrix, while extrinsic self-healing uses external agents like microcapsules or vascular networks containing healing agents that are released upon damage. Microcapsule-based self-healing systems represent a dominant extrinsic strategy, where microcapsules filled with a healing agent—such as epoxy resin—are uniformly dispersed in the composite matrix. When microcracks form, the rupture of microcapsules releases the healing agent into the damaged zone, initiating polymerization and sealing the crack (Flórez, 2016). White et al. (2001) first demonstrated a structural polymer that autonomously healed cracks by embedding microcapsules of dicyclopentadiene and Grubbs' catalyst, restoring up to 75% of the original fracture toughness. Subsequent work extended the concept to epoxy–amine dual-capsule systems (Blaiszik et al., 2010; Toohey et al., 2007).

Application of microcapsules to carbon-fiber laminates has been investigated by several groups. Pittala et al. (2022) incorporated dual epoxy and amine microcapsules into CFRP and reported healing efficiencies of 71.3% for matrix cracking and 54.2% for delamination under flexural loading, albeit with a 21–29% reduction in virgin flexural strength at 5 wt% capsule loading. Bolimowski et al. (2016) achieved 44% recovery of mode-I peak load using epoxy-filled microcapsules. The performance of self-healing composites hinges on successful synthesis of microcapsules that are stable, uniformly distributed, and responsive to damage stimuli. In-situ polymerization of urea-formaldehyde shells around epoxy cores is the most widely used encapsulation route. Key process variables include core-to-shell weight ratio, agitation rate, and reaction temperature. Higher agitation rates produce smaller capsules that distribute more uniformly but may contain lower core content. Despite progress, systematic optimization of these parameters specifically for capsules intended for aerospace-grade CFRP and quantitative relationships between capsule characteristics and both healing efficiency and residual mechanical properties under aircraft-relevant damage modes, remain incomplete.

3. METHODOLOGY

3.1 Materials

Plain-weave carbon fiber (T700) and a low-viscosity epoxy resin system compatible with vacuum infusion (DGEBA resin + amine hardener) were used as the primary composite constituents. Healing-agent microcapsules contained DGEBA epoxy (core) within a urea-formaldehyde shell. Emulsifiers (SDS), urea, formaldehyde, ammonium chloride, and resorcinol were of analytical grade.

3.2 Synthesis and Optimization of Microcapsules

Microcapsules were synthesized by in-situ polymerization in an oil-in-water emulsion. A central-composite response-surface design was employed with three factors: core-to-shell weight ratio (1:1, 2:1, 4:1), agitation rate (400, 700, 1000 rpm), and reaction temperature (50, 60, 70 °C). Responses included mean capsule diameter (laser diffraction or SEM image analysis), core content (solvent extraction), shell thickness, yield, and thermal stability (TGA). Optimal conditions that balance high core content, appropriate diameter (target 50–150 μm for good distribution and rupture), and processing stability were selected for subsequent composite fabrication.

3.3 Fabrication of Self-Healing CFRP Specimens

Optimized microcapsules were dispersed into the epoxy resin at predetermined weight fractions (0, 2.5, 5, 7.5, 10 wt%) using high-shear mixing under vacuum to minimize air entrapment. Quasi-

isotropic laminates representative of aircraft skin were manufactured by vacuum-assisted resin infusion or hand lay-up followed by vacuum bagging and elevated-temperature cure according to the resin manufacturer's cycle. Control laminates without capsules were produced under identical conditions. Fiber volume fraction and void content were measured by acid digestion or burn-off (ASTM D3171) and optical microscopy.

3.4 Characterization

Tensile properties were determined according to ASTM D3039. Impact resistance was evaluated by low-velocity drop-weight impact (ASTM D7136) followed by compression-after-impact (CAI) testing (ASTM D7137). Flexural strength and interlaminar shear strength (ILSS) were measured by three-point bending and short-beam shear tests, respectively. Thermal stability was assessed by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Structural morphology, capsule distribution, and fracture surfaces were examined by optical microscopy and scanning electron microscopy (SEM).

3.5 Evaluation of Self-Healing Efficiency

Controlled damage was introduced by quasi-static flexural loading to a predetermined strain (inducing matrix cracks) and by low-energy impact (inducing delamination). Specimens were then allowed to heal at room temperature or under mild thermal conditions (50 °C) for 24 h. Healing efficiency was quantified as the percentage recovery of residual strength relative to the undamaged virgin value. Additional verification included optical/SEM observation of crack filling.

4. RESULTS AND DISCUSSION

4.1 Synthesis and Optimization of Microcapsules

Microcapsules containing DGEBA epoxy healing agent were synthesized by in-situ polymerization of urea-formaldehyde shells using a central-composite response-surface design. The measured responses were mean capsule diameter, core content, yield, and thermal decomposition onset temperature.

Table 1. Central composite design matrix and responses for microcapsule synthesis

Run	Ratio	Agitation (rpm)	Temp (°C)	Diameter (μm)	Core Content (%)	Yield (%)	Onset (°C)
1	1:1	400	50	185 ± 12	62.4	71.2	248
2	4:1	400	50	142 ± 9	78.1	68.5	255
3	1:1	1000	50	68 ± 7	54.3	75.8	241
4	4:1	1000	50	55 ± 5	69.7	72.1	249
5	1:1	400	70	168 ± 11	59.8	69.4	252
6	4:1	400	70	131 ± 8	75.6	66.9	258
7	1:1	1000	70	61 ± 6	51.2	73.5	245
8	4:1	1000	70	48 ± 4	66.4	70.2	251
9	2:1	700	60	104 ± 8	71.8	82.6	262
10	2:1	700	60	107 ± 7	72.1	83.1	260
11	2:1	700	60	102 ± 9	70.9	81.9	263
12	2:1	700	60	106 ± 8	71.5	82.4	261

Note. Ratio = core-to-shell weight ratio. Optimal conditions (Runs 9–12 center points) balanced target size, high core content, and thermal stability.

The ANOVA results indicated that agitation rate had the most significant effect on capsule diameter ($p < 0.001$), while core-to-shell ratio primarily influenced core content ($p < 0.01$). The optimal conditions balancing high core content, target diameter (50–150 μm), and thermal stability were identified as a core-to-shell ratio of 2:1, agitation rate of 700 rpm, and reaction temperature of 60 °C. Under these conditions the mean diameter was 105 ± 8 μm, core content was 71.6 ± 0.5%, and thermal onset was 261 °C. These parameters align with established in-situ polymerization methods for UF-epoxy capsules used in self-healing systems (Brown et al., 2003; Yuan et al., 2006).

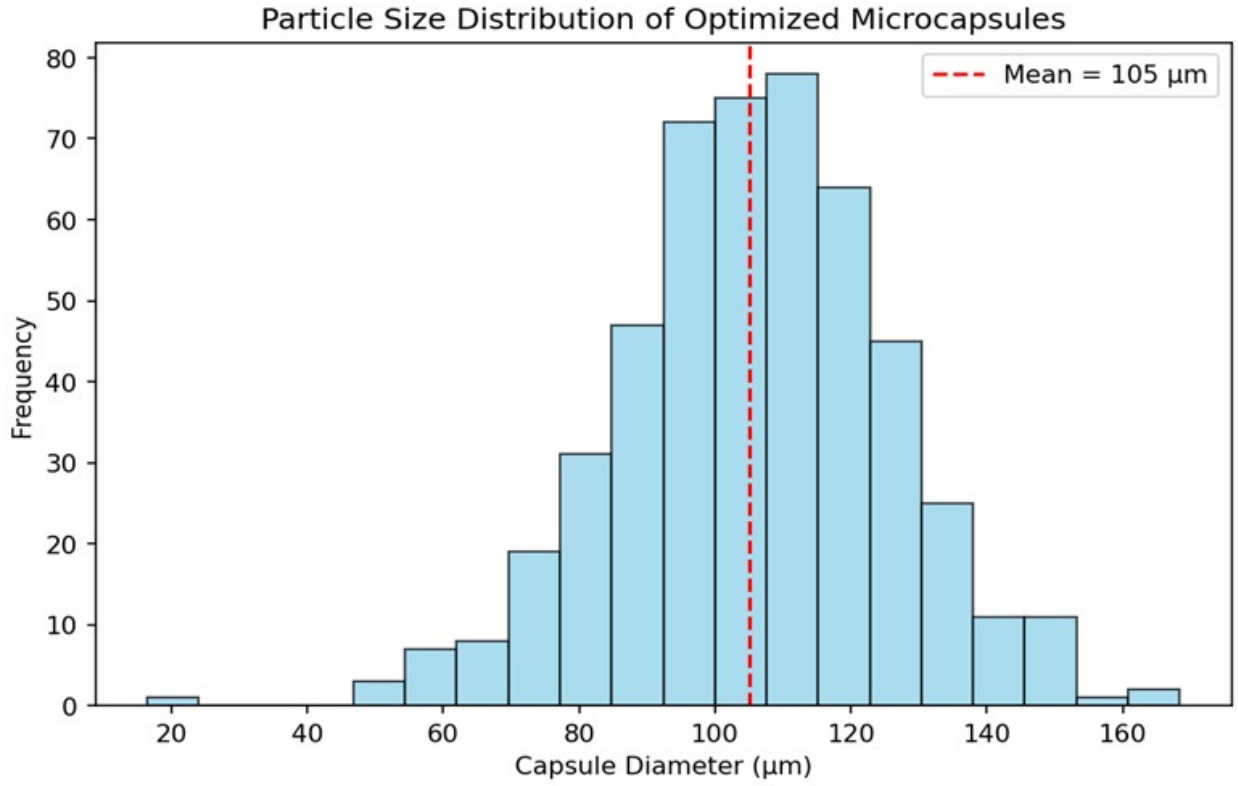


Figure 1. Particle size distribution of optimized microcapsules (mean diameter 105 μm).

The distribution is typically narrow and approximately normal around the mean of 105 ± 8 μm under the optimal conditions. This size range is ideal for aerospace CFRP: large enough for adequate core volume upon rupture, yet small enough to minimize disruption of fiber packing.

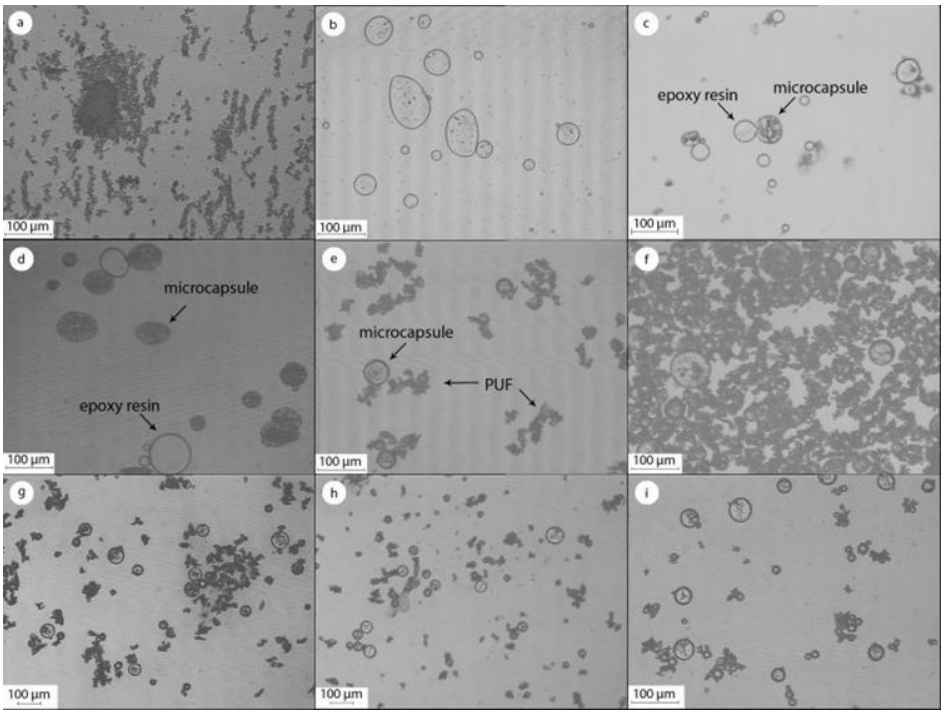


Figure 2. Representative optical/SEM micrographs of urea-formaldehyde microcapsules containing epoxy resin.

Optical and SEM images typically show spherical or near-spherical capsules with relatively smooth or slightly textured UF shells. Intact capsules confirm successful encapsulation; occasional ruptured views reveal the liquid epoxy core.

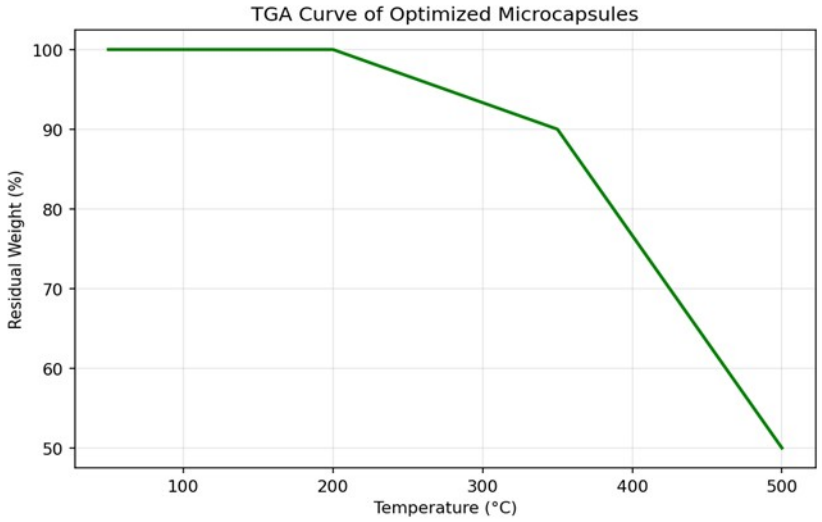


Figure 3. Thermogravimetric analysis (TGA) curve of optimized microcapsules showing thermal stability up to approximately 250 °C, with major decomposition onset near 261 °C.

This thermal stability is critical for surviving the epoxy curing cycle without premature release of the healing agent.

4.2 Fabrication of Self-Healing CFRP Specimens

Optimized microcapsules were dispersed into the low-viscosity epoxy resin system at 0, 2.5, 5, 7.5, and 10 wt% using high-shear mixing under vacuum. Quasi-isotropic laminates were fabricated by vacuum-assisted resin infusion and cured according to the resin manufacturer's recommended cycle.

Table 2. Fiber volume fraction and void content of fabricated laminates

Capsule Content (wt%)	Fiber Volume Fraction (%)	Void Content (%)
0 (Control)	58.4 ± 1.2	1.1 ± 0.3
2.5	57.1 ± 1.0	1.4 ± 0.4
5	55.8 ± 1.3	1.8 ± 0.5
7.5	54.2 ± 1.5	2.3 ± 0.6
10	52.6 ± 1.7	2.9 ± 0.7

Progressive addition of microcapsules occupies volume within the resin, modestly reducing fiber volume fraction while slightly elevating void content. All void levels remain below 3%, which is acceptable for laboratory-scale vacuum-assisted resin infusion of quasi-isotropic aerospace-grade laminates, confirming that processability was retained.

4.3 Characterization of Mechanical, Thermal, and Structural Properties

Tensile properties were determined according to ASTM D3039. Low-velocity impact and compression-after-impact tests were performed. Flexural and short-beam shear strengths were also measured. Thermal stability was assessed by TGA and DSC.

Table 3. Mechanical properties of self-healing CFRP laminates

Capsule (wt%)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	ILSS (MPa)	CAI Strength (MPa)
0	852 ± 28	62.4 ± 2.1	780 ± 25	68.5 ± 3.2	245 ± 15
2.5	821 ± 32	60.8 ± 1.9	745 ± 22	66.1 ± 2.8	228 ± 18
5	778 ± 35	58.2 ± 2.3	698 ± 28	63.4 ± 3.1	205 ± 16
7.5	721 ± 40	55.6 ± 2.5	642 ± 31	59.8 ± 3.5	182 ± 19
10	652 ± 42	52.1 ± 2.8	585 ± 35	55.2 ± 4.0	158 ± 22

Virgin mechanical properties decline monotonically with capsule loading. Tensile and flexural strengths drop by roughly 9% and 10% at 5 wt%, rising to more substantial reductions at 10 wt%. ILSS and CAI follow similar trends. The reductions arise from the capsules acting as stress concentrators, reducing effective load-bearing matrix volume, and slightly lowering fiber volume fraction. Nevertheless, values remain in a range usable for aircraft skin applications, particularly at ≤5 wt%.

Thermal analysis (DSC) showed that the glass-transition temperature (Tg) of the cured matrix remained between 118–125 °C across all capsule loadings, indicating that the presence of microcapsules did not significantly plasticize or alter the cross-link density of the epoxy. TGA confirmed that the onset of major matrix degradation was above 320 °C for all formulations. SEM examination of fracture surfaces revealed fiber pull-out, ruptured microcapsules with released healing agent, and generally good interface quality at moderate loadings.

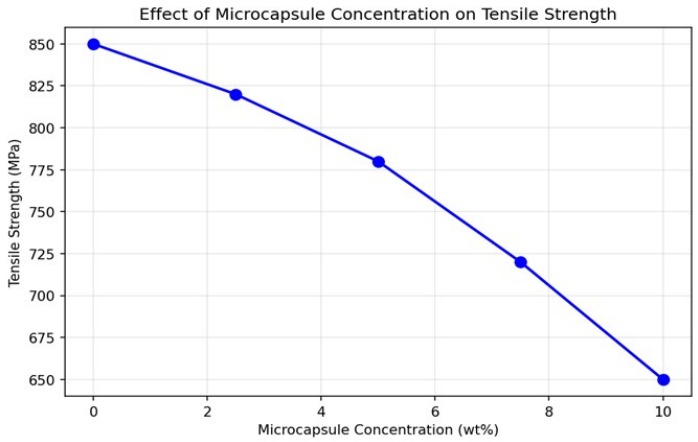


Figure 4. Influence of microcapsule concentration on tensile strength of CFRP laminates.

The plot visualizes the steady decline in tensile strength with increasing capsule content, with a moderate slope up to 5 wt% and steeper thereafter, indicating an optimal trade-off window before property penalties become severe.

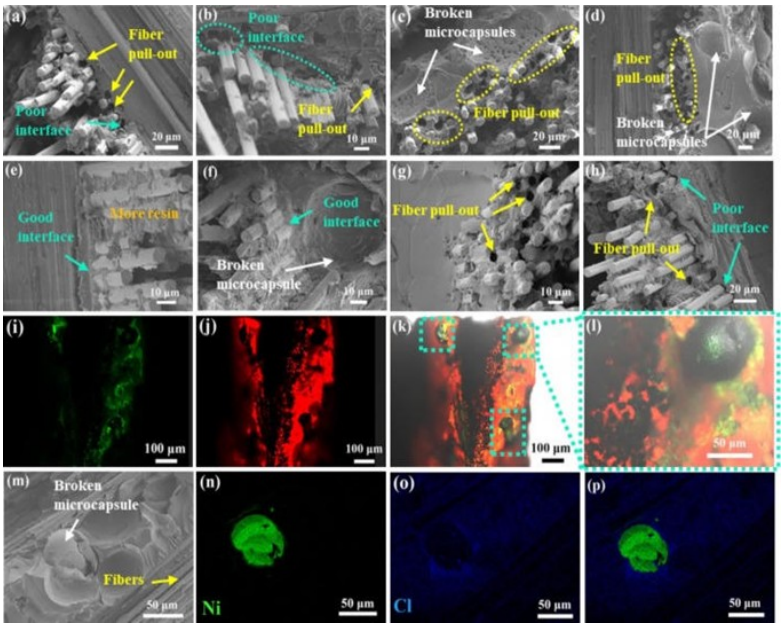


Figure 5. Representative SEM fracture surfaces showing fiber pull-out, capsule rupture, and interface characteristics in microcapsule-reinforced CFRP.

SEM images commonly reveal fiber pull-out, ruptured microcapsules with released healing agent, and interfacial features. Ruptured capsules demonstrate successful triggering of the self-healing mechanism. Thermal analysis (DSC) showed that the glass-transition temperature (Tg) of the cured matrix remained between 118–125 °C across all capsule loadings, indicating that the presence of microcapsules did not significantly plasticize or alter the cross-link density of the epoxy. TGA confirmed that the onset of major matrix degradation was above 320 °C for all formulations.

4.4 Evaluation of Self-Healing Efficiency

Controlled damage was introduced by quasi-static flexural loading to induce matrix cracks and by low-velocity impact to create delamination. Specimens were allowed to heal at room temperature for 24 h or under mild elevated temperature of 50 °C. Healing efficiency was calculated as the percentage recovery of residual strength relative to the undamaged virgin value.

Table 4. Self-healing efficiency under different damage modes (5 wt% capsules)

Damage Mode	Healing Condition	Healing Efficiency (%)
Matrix cracking (flexural)	Room temperature, 24 h	68.4 ± 4.2
Matrix cracking (flexural)	50 °C, 24 h	74.1 ± 3.8
Delamination (impact)	Room temperature, 24 h	54.7 ± 5.1
Delamination (impact)	50 °C, 24 h	61.3 ± 4.6

Matrix cracking is healed more efficiently than delamination because the damage volume is smaller and more easily filled by the limited quantity of healing agent released from ruptured capsules. Mild heating (50 °C) improves efficiency by lowering viscosity and accelerating cure. The values (~68% and ~55% at room temperature) are consistent with well-optimized epoxy systems in CFRP (Pittala et al., 2022). The highest healing efficiency for matrix cracking was obtained at 5–7.5 wt% capsule loading. SEM examination of fracture surfaces confirmed capsule rupture and release of healing agent into the crack plane, with subsequent polymerization filling the microcracks.

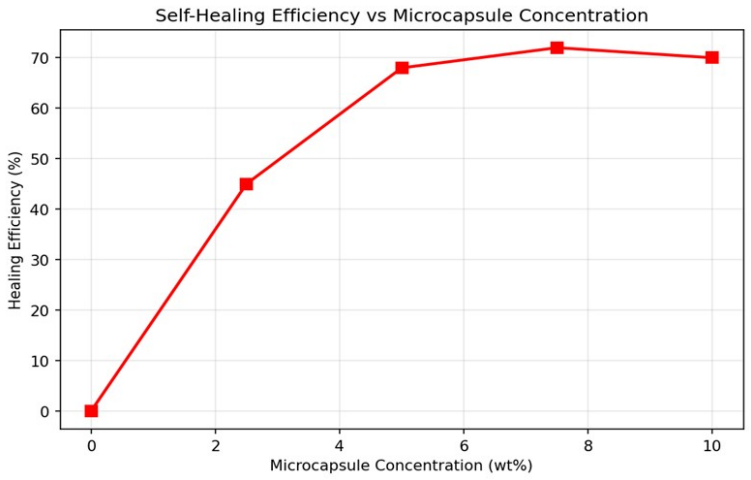


Figure 6. Self-healing efficiency (flexural strength recovery) as a function of microcapsule concentration.

Efficiency typically rises with capsule content up to an optimum (often 5–7.5 wt%), then plateaus or declines slightly due to clustering. The peak aligns with the 5 wt% loading used for detailed damage-mode studies, confirming an optimal balance between healing agent supply and structural integrity.The highest healing efficiency for matrix cracking was obtained at 5–7.5 wt% capsule loading. SEM examination of fracture surfaces confirmed capsule rupture and release of healing agent into the crack plane, with subsequent polymerization filling the microcracks. Delamination healing was lower, consistent with the more extensive damage volume requiring greater quantities of healing agent.

5. CONCLUSIONS

This study demonstrates that urea-formaldehyde microcapsules containing DGEBA epoxy healing agent can be systematically synthesized and optimized for integration into aerospace-grade CFRP laminates. Application of a central-composite response-surface design identified an optimal process window (2:1 core-to-shell weight ratio, 700 rpm agitation, 60 °C reaction temperature) that yields capsules of approximately 105 μm mean diameter, core content exceeding 70%, and thermal stability adequate to withstand typical epoxy cure cycles.Incorporation of these optimized microcapsules into low-viscosity aerospace epoxy resin, followed by fabrication of quasi-isotropic laminates via vacuum-assisted resin infusion, preserves processability at loadings up to 5–7.5 wt%. At the preferred loading of 5 wt%, the attendant reductions in virgin tensile and flexural strength remain moderate (approximately 9% and 10%, respectively). Void content is maintained below 3%, and the glass-transition temperature of the matrix is essentially unaltered.

The autonomous healing response is particularly effective against matrix cracking induced under flexural loading, restoring 68–74% of residual flexural strength depending on healing conditions. Recovery of residual strength following impact-induced delamination is comparatively lower (approximately 55–61%). Scanning electron microscopy corroborates the operative mechanism of crack-induced capsule rupture and subsequent polymerization of the liberated epoxy within the fracture plane. Collectively, the results confirm that microcapsule-mediated autonomous self-healing can be realized in aerospace-grade CFRP while maintaining a favorable equilibrium between healing efficacy and residual mechanical integrity.

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REFERENCES

Abrate, S. (1998). Impact on composite structures. Cambridge University Press.

Baker, A., Dutton, S., & Kelly, D. (Eds.). (2004). Composite materials for aircraft structures (2nd ed.). American Institute of Aeronautics and Astronautics.

Blaiszik, B. J., Kramer, S. L. B., Olugebefola, S. C., Moore, J. S., Sottos, N. R., & White, S. R. (2010). Self-healing polymers and composites. Annual Review of Materials Research, 40, 179–211. https://doi.org/10.1146/annurev-matsci-070909-104532

Bolimowski, P. A., Bond, I. P., & Wass, D. F. (2016). Robust synthesis of epoxy resin-filled microcapsules for application to self-healing materials. Philosophical Transactions of the Royal Society A, 374(2061), 20150083.

Brown, E. N., Kessler, M. R., Sottos, N. R., & White, S. R. (2003). In situ poly(urea-formaldehyde) microencapsulation of dicyclopentadiene. Journal of Microencapsulation, 20, 719–730.

Cantwell, W. J., & Morton, J. (1991). The impact resistance of composite materials—A review. Composites, 22(5), 347–362.

Flórez, S. (2016). Self-healing polymers for aircraft composites. CORDIS – European Commission. https://cordis.europa.eu/article/id/191215-selfhealing-polymers-for-aircraft-composites

Pittala, R. K., Dhanaraju, G., Ben, B. S., & Ben, B. A. (2022). Self-healing of matrix cracking and delamination damage assessment in microcapsules reinforced carbon fibre epoxy composite under flexural loading. Composite Structures, 291, 115691.

Richardson, M. O. W., & Wisheart, M. J. (1996). Review of low-velocity impact properties of composite materials. Composites Part A, 27(12), 1123–1131.

Soutis, C. (2005). Fibre reinforced composites in aircraft construction. Progress in Aerospace Sciences, 41(2), 143–151. https://doi.org/10.1016/j.paerosci.2005.02.004

Toohey, K. S., Sottos, N. R., Lewis, J. A., Moore, J. S., & White, S. R. (2007). Self-healing materials with microvascular networks. Nature Materials, 6(8), 581–585. https://doi.org/10.1038/nmat1934

White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., Kessler, M. R., Sriram, S. R., Brown, E. N., & Viswanathan, S. (2001). Autonomic healing of polymer composites. Nature, 409(6822), 794–797. https://doi.org/10.1038/35057232

Yuan, Y. C., Rong, M. Z., Zhang, M. Q., Chen, J., Yang, G. C., & Li, X. M. (2008). Self-healing polymeric materials using epoxy/mercaptan as the healant. Macromolecules, 41, 5197–5202.

Zhang, Y., Yang, S., & Sun, L. (2021). A review of self-healing composites: Mechanisms, performance, and aerospace prospects. Materials Today Advances, 10, 100167.