

The Phoenix Effect: Resilient Vitrimers and the Future of Self-Healing, Circular Electronics

Siddharth Panigrahy¹, Disha Patil¹, Rutuja Aher¹, Mansi Waldia¹, Preeti Zade^{2*} and S.N. Zade³

¹ Undergraduate Students, Department of Computer Engineering, Terna Engineering College, Navi Mumbai, India

² Professor, Department of Science and Humanities, Terna Engineering College, Navi Mumbai, India

³ Associate Professor, Department of Humanities and Sciences, A.C.Patil College of Engineering, Navi Mumbai, India

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ABSTRACT

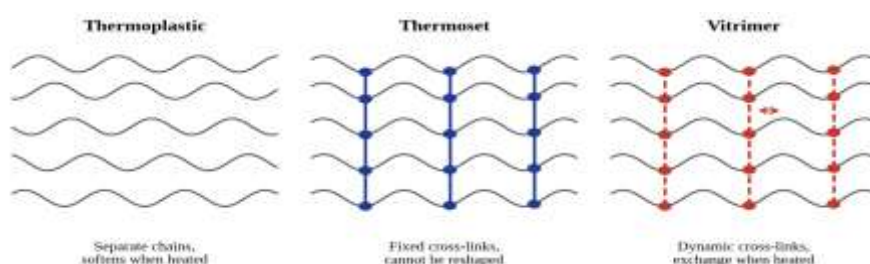
Electronic devices may be discarded when a polymer component cracks, even if much of the device remains functional. Vitrimers are covalent adaptable polymer networks that can retain a cross-linked structure while allowing bond exchange under suitable conditions. This study examines their potential for repairable electronic components and considers a preliminary tensile-recovery result for a vitrimer formulation. The treatment condition considered was 80 °C for 30 minutes. A healing-efficiency value of 93.5% was reported in the preliminary study, but the underlying specimen-level tensile measurements and statistical analysis are not available in the current manuscript; the value is therefore preliminary and not independently verifiable here. The manuscript defines the calculation, identifies the experimental details needed for reproducibility, and distinguishes measured evidence from proposed applications. Healing at ordinary smartphone charging temperatures has not been demonstrated. Longer service life, recyclability and environmental benefits remain possibilities that require device-level testing, recycling studies and life-cycle assessment.

Keywords: Vitrimers; self-healing polymers; dynamic covalent bonds; tensile recovery; electronic components; circular economy

INTRODUCTION

Plastics are used in electronic housings, frames, encapsulants and other components. A crack in one component can lead to repair or replacement, depending on its function and the damage location. Thermoplastics can generally be softened and reshaped by heating, whereas conventional thermosets contain permanent cross-links and cannot simply be remelted. Vitrimers are covalent adaptable networks in which exchange reactions can permit network rearrangement while maintaining connectivity over relevant timescales [1, 2, 5, 6]. Their response depends on network chemistry, catalyst, temperature and the timescale of the process.

Figure 1: Schematic comparison of thermoplastic, thermoset and vitrimer polymer networks



Self-healing polymers are being investigated as a way to recover function after damage. Some systems release healing agents into a crack, while others rely on reversible interactions or dynamic covalent bonds [7, 8]. Vitrimers are of interest because exchange reactions may allow a damaged interface to reconnect under appropriate conditions [1, 6]. However, visual crack closure alone does not establish mechanical recovery. A robust assessment requires controlled damage, a defined healing treatment, replicate mechanical testing and uncertainty estimates.

Table 1: Examples of self-healing materials in electronic devices

Device category	Examples of components	Role of self-healing
Electronic accessories	Actuators, transistors	Restores mechanical and electrical function after damage
Energy harvesting	Perovskite solar cells, nanogenerators	Extends operating life of thin, flexible layers
Energy storage	Lithium-ion batteries, supercapacitors	Reduces failure caused by cracking and fatigue
Bioelectronics	Sensors, electronic skin	Maintains sensing performance after repeated deformation

In a vitrimer, dynamic covalent bonds can exchange partners through reactions such as transesterification, allowing topology rearrangement under suitable conditions [1, 5, 6]. The temperature and rate of exchange depend on formulation and test conditions; a single temperature cannot be assumed to activate every vitrimer. The topology-freezing temperature, T_v , must be defined and measured using a stated method before the treatment temperature can be compared with it.

OBJECTIVES

The aim of this study is to examine the potential of vitrimer networks for thermally assisted repair and to identify the evidence needed to evaluate mechanical recovery. The specific objectives are to:

- Explain the mechanism: describe how dynamic covalent bonds can permit network rearrangement without melting the material as a conventional thermoplastic would.
- Assess mechanical recovery: define tensile-strength healing efficiency and report the preliminary value only with appropriate qualification until raw measurements and uncertainty estimates are available.
- Consider an electronics application: evaluate a smartphone internal frame as a conceptual future application, not as a demonstrated device.
- Discuss circularity responsibly: identify repairability as a potential contribution to longer service life while recognising that recyclability and environmental benefits require separate evidence.

METHODOLOGY

The study examines the proposed use of a vitrimer for thermally assisted repair through formulation and specimen preparation, controlled damage, thermal treatment, tensile testing and microscopy. The information available for this manuscript does not include all procedural records required for independent reproduction. Missing experimental details are stated as limitations rather than estimated.

Preparation of the vitrimer

The formulation was described as a bio-based epoxy vitrimer. The precise resin and hardener identities, stoichiometric ratio, catalyst identity and loading, supplier details, and supporting evidence for bio-based content must be stated to make the formulation reproducible. Published bio-based vitrimer formulations

demonstrate that such chemistries are possible, but they do not establish the composition of the material used in this study [3].

Controlled damage

The specimens were described as rectangular dog-bone samples, and a blade was used to introduce damage. The specimen standard, dimensions, damage location and depth, blade specification and conditioning procedure were not documented in the available material. The damage procedure therefore cannot be reproduced precisely.

Healing treatment

The treatment condition used in the preliminary study was 80 °C for 30 minutes. The actual specimen temperature, heating equipment, applied pressure or clamping force, and cooling procedure must be documented. The relation between 80 °C and the material's topology-freezing temperature, T_v , has not been established in the available manuscript. Therefore, this treatment is not described as being above T_v .

Tensile testing and microscopy

Formulation And Processing

The available project description identifies the material as a bio-based epoxy vitrimer, but does not specify the resin and hardener grades, stoichiometric ratio, catalyst identity or loading, or mixing and degassing procedure. These formulation details are therefore not reported, and the composition cannot be reproduced from the information currently available.

Cure And Specimen Preparation

The cure and post-cure schedules, exact dog-bone specimen dimensions, mould details and conditioning procedure are not specified in the available description. These parameters should not be inferred, because they can affect the mechanical properties and comparability of the results.

Tensile Testing

The tensile-test standard, instrument and load-cell capacity, crosshead rate, test temperature, specimen dimensions, failure criterion and replicate counts are not available. Consequently, the reported healing-efficiency value cannot be independently recalculated or statistically assessed.

Healing Treatment

The treatment condition considered was 80 °C for 30 minutes. The heating equipment, actual specimen temperature, applied pressure or clamping force, and cooling procedure are not specified. No assumption is made about whether pressure or clamping was applied.

Topology-Freezing Temperature (T_v)

The topology-freezing temperature (T_v) was not measured or documented in the available study information. The relationship between T_v and the 80 °C treatment condition is therefore unknown; the treatment temperature is not described as being above T_v .

Tensile strength was intended to be compared across virgin and healed specimens. Because the test standard, instrument, load-cell capacity, crosshead rate, test temperature, specimen dimensions, failure criterion and replicate count are not documented, the mechanical results cannot be independently assessed. No statistical significance is claimed.

Case Description

A smartphone internal frame is considered here as a conceptual application. The scenario is intended to illustrate a possible use of a repairable polymer, not to report a tested smartphone component.

The problem: gradual damage to the frame

A crack in a frame or support component can affect alignment or mechanical integrity, but the consequence depends on the device design, crack location and loading conditions.

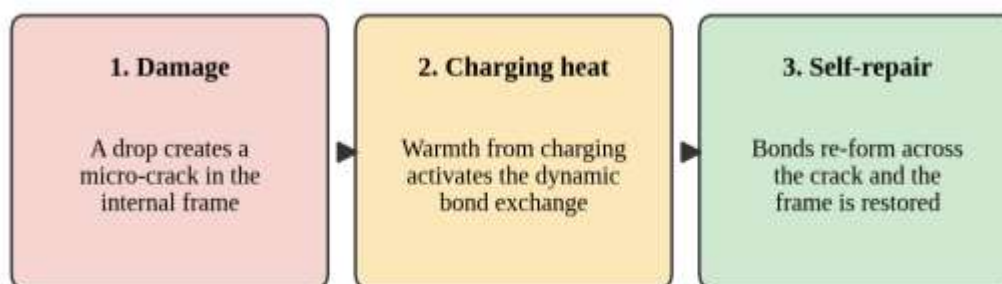
- Repeated mechanical loading may cause an existing crack to grow. The rate and consequence of crack growth must be established for the specific component and material.
- If a component fails, repair or replacement may be required. This study does not quantify device failure rates or replacement decisions.
- Repairability could reduce the need to replace a component, but this outcome depends on repair success, safety, durability and the practical repair process.

The proposed solution: using charging heat

The proposed sequence is conceptual: damage occurs, a suitable repair treatment is applied, and the component is tested to establish whether function has recovered. The laboratory treatment considered here was 80 °C for 30 minutes; healing at ordinary smartphone charging temperatures has not been demonstrated.

1. A drop or repeated loading could initiate a crack in a polymer frame; this is a proposed scenario, not an observed device test.
2. During charging, smartphone temperatures depend on the device, ambient conditions, battery state and charging power.
3. Normal charging heat must not be assumed to activate the vitrimer. A formulation that heals at those temperatures, and its compatibility with the battery and electronics, would need to be demonstrated experimentally.

Figure 2: Proposed self-repair sequence for a smartphone internal frame



The proposed charging-based repair depends on a material that can heal at the temperatures reached safely within a device. This has not been demonstrated. The reported laboratory treatment of 80 °C for 30 minutes does not establish healing under ordinary charging conditions.

Table 2. Availability Of Tensile-Strength Data

Table 2 summarises the status of the tensile evidence available for this manuscript. The missing observations are reported as unavailable rather than replaced with estimated or simulated values.

Specimen group	Sample size (n)	Individual tensile strengths	Mean ± SD
Virgin	Not reported	Not available	Not calculable

Damaged	Not reported	Not available	Not calculable
Healed	Not reported	Not available	Not calculable

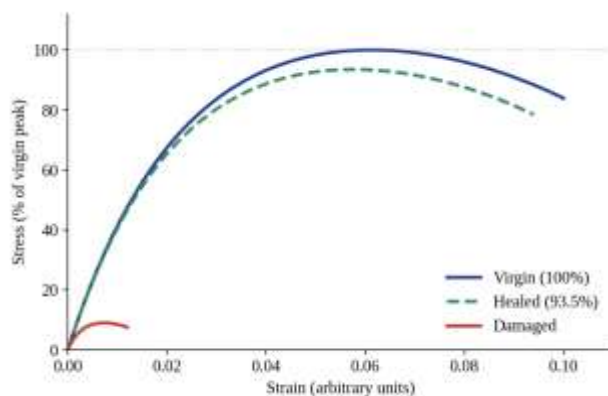
Potential benefit: reparability could contribute to longer service life if a safe, repeatable repair process is demonstrated.

No device-level lifetime result is available. The manuscript therefore makes no numerical prediction for how many years a phone would last. Any claim of longer service life requires device-level mechanical, thermal, electrical and safety testing.

Analysis

Three specimen conditions are relevant to the evaluation: virgin, damaged and healed. Figure 3 is retained as a schematic to explain the comparison; it is not measured stress–strain data. Measured curves must be generated from the original force–displacement records and specimen dimensions before quantitative mechanical conclusions are drawn.

Figure 3: Schematic comparison of virgin, damaged and healed stress–strain behaviour; illustrative only, not measured data.



- Virgin specimens would provide the reference tensile strength. Individual measurements and the sample size are not available in the current manuscript.
- Damaged specimens would characterise the effect of the specified damage procedure. No quantitative conclusion about their residual strength is drawn without measured values.
- A healing-efficiency value of 93.5% was reported in the preliminary study. The specimen-level data, replicate count and uncertainty estimates are not included in this manuscript, so the value remains preliminary and cannot yet be independently verified.

Healing efficiency (η) is defined as the tensile strength after healing divided by the virgin tensile strength, expressed as a percentage:

$$\eta = (\sigma_{\text{healed}} / \sigma_{\text{virgin}}) \times 100 \quad (1)$$

The reported 93.5% value remains preliminary because the individual specimen measurements, sample sizes and uncertainty estimates are unavailable. The value should be interpreted as a reported preliminary figure, not as a statistically validated result.

Microscopy And Crack-Width Analysis

Calibrated micrographs of virgin, damaged and healed specimens, with scale bars and quantitative crack-width measurements, are not available in the current manuscript. The extent of crack closure and the condition of the healed interface therefore cannot be verified from microscopy.

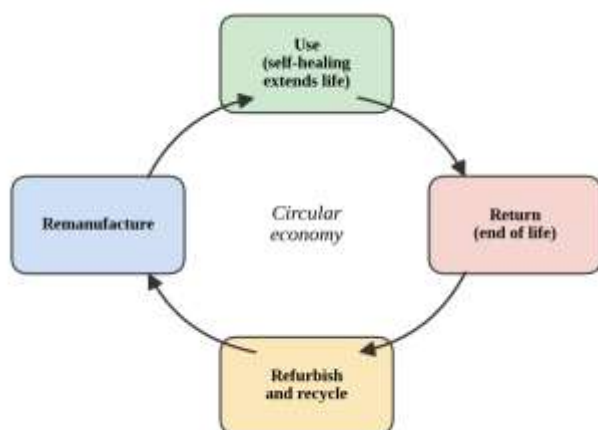
FINDINGS

The current evidence supports a cautious discussion of the material concept, not definitive claims about performance. The following distinctions apply:

1. Temperature dependence: bond exchange is formulation- and timescale-dependent. T_v was not established in the available manuscript, so the study cannot conclude that healing occurs only above a measured T_v or that 80 °C exceeds it.
2. Microscopy: no calibrated virgin, damaged and healed image set or crack-width measurements are included in the current manuscript. Complete crack disappearance and the absence of a weak seam are therefore not established.
3. Service life: repairability could contribute to longer service life, but no two-to-ten-year lifetime projection is retained. Device-level durability and safety testing are required.

Circularity: a repairable component may be relevant to circular design, but recyclability and environmental superiority are not established by healing efficiency alone [4].

Figure 4: Circular economy loop for electronic devices (own schematic based on the concept in [4])



CONCLUSION

Vitrimers are a promising class of covalent adaptable networks for investigating thermally assisted repair of cross-linked polymers. This manuscript considers a treatment condition of 80 °C for 30 minutes and records a preliminary healing-efficiency value of 93.5%. However, individual tensile measurements, replicate counts and uncertainty estimates are not available in the current document, so the reported value cannot be independently verified and should not be treated as a validated quantitative result. The formulation, tensile-test procedure, microscopy evidence and topology-freezing temperature also require fuller documentation before the experiment can be reproduced. Healing at ordinary smartphone charging temperatures has not been demonstrated, and the smartphone-frame concept remains a proposed application. Repairability could contribute to longer component service life, but this requires device-level mechanical, thermal and safety testing. Claims about recyclability or environmental benefit require recycling studies and life-cycle assessment. The conclusions are therefore limited to the material concept and the preliminary report; stronger performance claims require complete, replicated experimental evidence.

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