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INVESTIGATION OF THE PHYSICAL PROPERTIES AND HEALING MECHANISMS OF SELF-HEALING MATERIALS

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Abstract: This article analyzes the physical mechanisms, classification and structural characteristics of self-healing materials. The operating principles of extrinsic and intrinsic self-healing materials, the physical foundations of dynamic covalent and non-covalent bonding, and the mechanisms by which microcapsule and vascular systems autonomously heal damage are examined.

Keywords: self-healing materials, extrinsic healing, dynamic covalent bonds, microcapsules, nanotechnology, graphene, Uzbekistan.

Introduction. Self-healing materials are a class of materials capable of restoring their original mechanical, electrical or chemical properties, either autonomously or with minimal external stimulation, after mechanical damage such as cracking, scratching or fracture [1]. The primary goals of these materials are to extend the service life of products, to reduce maintenance and repair costs, and to improve the operational safety of structures and components [2].

The concept of self-healing is directly inspired by living nature (biomimetics). Biological processes such as the spontaneous closure of a cut in human skin, the rejoining of bones after a fracture, and the regeneration of damaged plant tissue have motivated efforts to achieve similar behavior in artificial materials [3]. Research led by Nobel laureate Professor Kostya Novoselov has shown that graphene is capable of spontaneously healing holes in its lattice [4].

Physicochemical research on modern self-healing materials has developed rapidly over the last twenty years and has become one of the most promising directions in materials science [5]. The first fundamental study was carried out in 2001 by White and Sottos, who created polymer composites based on microcapsules [1]. Today, various strategies for imparting self-healing capability to materials have been developed, including extrinsic approaches (microcapsules and vascular networks) and intrinsic approaches (dynamic covalent and non-covalent bonds) [6, 7].

METHODOLOGY

This study was based on a systematic review and comparative analysis of the scientific literature on the physics of self-healing materials. Its main objective was to determine the physical parameters of different healing mechanisms, to compare them with one another, and to identify the most effective strategies.

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The scientific sources were selected in the following stages.

Stage 1: database search. The Scopus, Web of Science, Google Scholar and ResearchGate databases were searched using the keywords “self-healing materials,” “self-healing polymers,” “extrinsic healing,” “intrinsic healing,” “dynamic covalent bonds,” “non-covalent interactions,” “microcapsules” and “vascular networks.” The search covered the period 2000–2025.

Stage 2: screening of sources. From the more than 200 sources identified, those directly relevant to the topic of the article were selected. Primary attention was given to papers that reported experimental results and were published in reputable journals.

Stage 3: selection of local sources. Materials from the scientific journals of the Academy of Sciences of the Republic of Uzbekistan, the Uzbek Journal of Chemistry and the Journal of Materials Science were examined. Local studies on self-healing materials and nanotechnology were analyzed.

Data processing methods

The following data were extracted from each analyzed study: material type, healing mechanism, dynamic bonds employed, healing efficiency (%), healing temperature (°C), healing time (hours or days), diffusion coefficient (m^2/s) and mechanical strength (MPa). On this basis, mean values were calculated for each healing mechanism and material class. To enable comparison of results across different sources, the healing efficiency and mechanical strength values were standardized. To assess the effect of nanofillers, the differences between the indicators of the neat material and of the nanofiller-containing material were expressed in relative units.

RESULTS

Fifteen scientific sources were analyzed in the course of the study. The results obtained are presented below.

Physical characteristics of dynamic bonds

Healing efficiency, healing temperature and bond energy were examined for the different types of dynamic bonds. The results are presented in Table 1.

Table 1. Physical characteristics of dynamic bonds

Bond type	Bond energy (kJ/mol)	Healing temperature (°C)	Healing efficiency (%)
Hydrogen bond	4–30	20–60	70–90
Imine bond	100–150	50–80	70–90
Metal–ligand coordination	50–200	60–100	75–95

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Bond type	Bond energy (kJ/mol)	Healing temperature (°C)	Healing efficiency (%)
Disulfide bond	150–250	60–120	80–98
Diels–Alder reaction	100–200	80–120	85–99

According to the table, the highest healing efficiency was observed in materials based on Diels–Alder reactions (85–99%). These materials heal at temperatures of 80–120 °C. Materials based on disulfide bonds also showed high efficiency (80–98%). Materials based on hydrogen bonds have the advantage of operating at relatively low temperatures (20–60 °C), but their healing efficiency (70–90%) is lower than that of Diels–Alder and disulfide systems. Materials based on metal–ligand coordination exhibit intermediate values of temperature (60–100 °C) and efficiency (75–95%).

Comparative analysis of extrinsic and intrinsic mechanisms

In materials with an extrinsic mechanism, the microcapsule diameter ranged from 50 to 200 micrometers, and the average healing efficiency was 82%. The highest efficiency, 95%, was achieved at 80 °C. The main drawback of this mechanism was found to be that it can operate only once.

Among materials with an intrinsic mechanism, polymers based on disulfide bonds showed a healing efficiency above 90%, and polymers based on the Diels–Alder reaction reached 98%. The intrinsic mechanism allows up to five repeated healing cycles.

Effect of nanofillers

The addition of nanofillers considerably increased both healing efficiency and mechanical strength. When 0.5% graphene was added to the polymer matrix, healing efficiency increased by 25% and mechanical strength by 40%. With 1% carbon nanotubes, the increases were 30% and 50%, respectively, and with 0.8% MXene, 35% and 45%, respectively.

DISCUSSION

The results of the study provide important information on the physical mechanisms of self-healing materials and their effectiveness. In this section, the results obtained are compared with the existing literature, their scientific and practical significance is analyzed, and recommendations for future research are developed.

Effectiveness of dynamic bonds

The results presented in Table 1 show that materials based on the Diels–Alder reaction have the highest healing efficiency (85–99%). This is explained by the thermal reversibility of the Diels–Alder reaction and its high selectivity during cycloaddition. White et al. (2001) reported that Diels–Alder-based polymers achieved healing efficiencies of up to 98% at 120 °C [1]. This result is consistent with our analysis.

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CONCLUSION

Based on the research conducted on the physics of self-healing materials, the following conclusions were drawn.

First conclusion. Self-healing materials fall into two main mechanistic classes: extrinsic (based on microcapsules and vascular networks) and intrinsic (based on dynamic covalent and non-covalent bonds). Intrinsic mechanisms are distinguished by their capacity for repeated healing.

Second conclusion. Among dynamic bonds, materials based on the Diels–Alder reaction exhibit the highest healing efficiency (85–99%). Disulfide-based materials also show high efficiency (80–98%). Hydrogen-bond-based materials have the advantage of operating at low temperatures (20–60 °C).

Third conclusion. The extrinsic mechanism enables rapid healing (from 30 minutes to 12 hours) but operates only once, and the embedded microcapsules reduce the mechanical properties of the material by 10–15%.

Fourth conclusion. The intrinsic mechanism allows 5–10 repeated healing cycles but requires elevated temperatures (60–120 °C) and longer times (1–24 h).

Fifth conclusion. Hybrid systems (combining covalent and non-covalent bonds) represent the most promising direction. They provide healing efficiency above 95% and mechanical strength 30% higher than that of neat polymers.

Sixth conclusion. Nanofillers markedly improve both healing efficiency and mechanical strength. Graphene (0.5%) increases efficiency by 25% and strength by 40%; carbon nanotubes (1%) by 30% and 50%, respectively; and MXene (0.8%) by 35% and 45%, respectively.

Seventh conclusion. Among material classes, polymers exhibit the highest healing efficiency (88% on average), compared with 70% for metals and 60% for ceramics.

Eighth conclusion. Multilayer graphene obtained from bio-based sources by Uzbek scientists accelerates wound healing by 30% and exhibits antibacterial properties. Vitrimers based on disulfide bonds, synthesized from local raw materials, have achieved a healing efficiency of 90%.

Ninth conclusion. Future research should focus on the artificial-intelligence-assisted design of new dynamic bonds, the development of low-temperature healing mechanisms, integration with 4D printing technologies, and the expansion of applications in biomedicine and electronics.

Tenth conclusion. In the future, self-healing materials will play an important role in construction, aviation, the space industry, mechanical engineering, biomedicine and electronics by extending product service life, reducing repair costs and improving operational safety.

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