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The influence of magnetic nanocomponents on the strength of textile fibers

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Abstract

The article describes the method of synthesis of magnetic nanomaterials based on a mixture of divalent and trivalent iron. The adhesion properties of nanocomponents to fibers of different natures have been determined. A model of the interaction of nanocomponents and textile fibers has been constructed. The mechanical characteristics of fibers in a normal state and fibers with a magnetic component addition have been determined. It has been proven that the content of nanocomponents in an amount of 0.2–0.5% of the fiber mass leads to an increase in the tensile strength by 35–60%. The process of increasing the strength is justified in the process of modeling the load of conventional fibers and fibers filled with nanomagnetic components. The results obtained allow to recommend the technology of nanomagnetic strengthening of fibers when they are used in textile or other functional materials.

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Keywords: High-strength textile fibers; magnetite nanocomposites; fiber reinforcement;, mechanical properties enhancement; nanotechnology in textiles.

1. State of art

Textile fibers are widely used in various industries. Engelbrecht-Wiggans and Forster (2023) demonstrated that the relevance of enhancing the strength of fibers used in composite materials is determined by the increasing requirements for the performance characteristics of modern structures. Since fibers are the main reinforcing element of composites and define their mechanical properties, improving their strength directly contributes to greater reliability, durability, and load resistance. Bnar et al. (2024) showed that this fact opens up opportunities for expanding the application areas of composites in high-tech industries (aviation, aerospace, automotive, shipbuilding, and energy), where the combination of high strength and low structural weight is particularly important. The use of high-strength fibers makes it possible to reduce the weight of products, which leads to energy savings and reduced negative environmental impact, while also ensuring economic feasibility by extending the service life of materials, as demonstrated by Pereira et al. (2024). Thus, Milling et al. (2025) proved that enhancing the strength of fibers in composite materials is one of the key directions in modern materials science, determining the competitiveness of innovative technologies and their further development.

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The use of textile fibers in the light industry also highlights the relevance of enhancing their strength. Clothing and textile products are constantly exposed to mechanical stresses (stretching, friction, abrasion, washing). Stronger fibers ensure a longer service life of products, reducing consumer expenses. The use of stronger fibers allows for waste reduction and increased production profitability, as proven by Abtew et al. (2025). Durable materials require fewer replacements, saving resources and reducing the costs of producing new products.

Improving the longevity of textiles reduces the need for frequent production of new goods, thereby lowering raw material and energy consumption. Fode et al. (2024) showed that this aligns with modern trends of sustainable development and the "green" economy.

For protective clothing (military, firefighting, construction), particularly strong fabrics are required, as demonstrated by Tian et al. (2025). In the production of composites and reinforced materials (e.g., in aerospace or automotive engineering), high-strength textile fibers serve as a key component.

Research by Tiago et al. (2025) showed that in medicine, strong biocompatible fibers are used in surgical sutures, implants, and prostheses. Modern trends (nanotechnology, development of high-performance materials) impose new requirements on textiles, as noted by Riabchykov et al. (2024). The competitiveness of manufacturers directly depends on their ability to create fibers with improved characteristics, among which strength is a fundamental indicator, as emphasized by Asri Peni et al. (2023).

Methods of enhancing the strength of textile fibers are explored in various directions. In particular, Aldroubi et al. (2023) propose the creation of composite fibers. A number of studies, including those by Muñoz-Blandón et al. (2023) and Hossain et al. (2024), propose new fibers with enhanced properties. The use of intelligent approaches, suggested by Riabchykov and Mytsa (2024), further improves the mechanical characteristics of textile fibers.

Strength properties, according to Zou et al. (2025), can be increased by applying special coatings. Pathak et al. (2024) showed that nanotechnologies can be used to create specialized coatings. One of the directions in the implementation of nanotechnologies in the textile industry is the use of magnetic materials based on divalent and trivalent iron oxides, as shown in studies by Riabchykov et al. (2023a). Such an approach can increase the strength and other performance indicators of textile fibers. Despite certain achievements in the use of nanotechnologies in textile fibers, Gui et al. (2025) note that the actual results remain fragmented.

This study aims to develop a technology for using mixtures of divalent and trivalent iron oxides to improve the strength of textile fibers.

2. Methods and materials

The first step toward the development of high-strength fibers consists in the synthesis of an Fe^{2+} /Fe^{3+} oxide mixture, commonly referred to as magnetite (Fe_3O_4). One of the most effective synthesis methods has been reported by Riabchykov et al. (2023b). This approach employs ferrous sulfate ($FeSO_4 \cdot 7H_2O$) and ferric chloride ($FeCl_3 \cdot 6H_2O$) as precursors.

Magnetite has the formula Fe_3O_4, which can be represented as a combination of Fe^{2+} and Fe^{3+} (formally $FeO \cdot Fe_2O_3$). Its formation requires a molar ratio of Fe^{2+} :Fe^{3+} = 1:2.

The heterogeneous reaction can be expressed as:

$$Fe^{2+} + 2\,Fe^{3+} + 8\,OH^- \rightarrow Fe_3O_4 + 4\,H_2O. \quad (1)$$

When $FeSO_4$ and $FeCl_3$ are used as ion sources, the corresponding spectator ions (SO_4^{2-}, Cl^-) remain in solution.

The synthesis procedure utilizes the following reagents: $FeSO_4 \cdot 7H_2O$, $FeCl_3 \cdot 6H_2O$, NaOH (or NH_4OH) aqueous solution, and deoxygenated distilled water. The required equipment includes a mechanical stirrer, a thermostated water bath (60–80 °C), a reaction vessel or flask with a hydrogen gas seal or under a nitrogen atmosphere, a magnet (for convenient recovery of ferrite particles), a filter, a centrifuge, washing flasks, and a pH meter.

A schematic representation of the magnetite synthesis process is shown in Fig. 1.

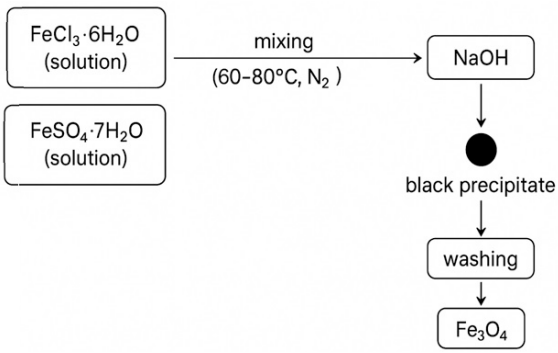


Fig. 1. Block diagram of magnetite synthesis.

The main properties of the obtained mixture (Fe_3O_4, Fe^{2+}/Fe^{3+} composite) can be summarized as follows.

Magnetic properties – the particles are attracted to a magnet; their properties depend on particle size. The structure of the mixture can be described as an inverse spinel. The density is approximately 5.17 $g \cdot cm^{-3}$.

The mixture is insoluble in water but dissolves in hydrochloric or sulfuric acids with the formation of Fe^{2+}/Fe^{3+} ions. The substance is stable in the absence of oxygen; upon exposure to oxygen, it oxidizes to γ-Fe_2O_3. The substance contains hydroxyl groups (–OH), which are useful for functionalization (binding organic molecules, polymers).

The obtained substance was applied to the surface of textile fibers according to the following procedure.

First, cleaning was carried out – washing in a neutral detergent solution to remove fats, waxes, and sizing agents. For natural fibers, additional treatment with a NaOH solution (mercerization) was performed. The resulting magnetite precipitate was dispersed in an aqueous-alcohol medium with stabilizers. The suspension concentration was typically 1–10 g/L.

The main coating method used was pad-dry. In this process, the textile was immersed in the dispersion, squeezed to the required wet pickup (70–100%), and dried at 80–100 °C. Thermofixation was carried out in a drying oven at 120–160 °C (for synthetics – below the melting point).

3. Main results

The modified fibers acquired a darker color, along with magnetic properties. Microscopic analysis showed a predominant localization of particles in the cavities and on the fiber surface (Fig. 2).

The images demonstrate the presence of quite pronounced clusters of components added to the fibers. Along with the uniform application of magnetite to the fiber surface, inclined dark stripes are observed. These stripes determine the increased density of the powder on the fiber surface. It should be noted that traditionally textile fibers have certain irregularities in the form of grooves and protrusions located around the circumference of the fiber. Such depressions form a system of concentrators that significantly reduce the potential strength of the fiber. Fig. 2 proves that the developed technology allows filling these irregularities with structures whose microstrength is higher than this indicator for the fiber material. The effect of added magnetite can be dual in nature. The first determines the application of a stronger material to the fiber surface. This strong material also fills the microirregularities on the fiber surface.

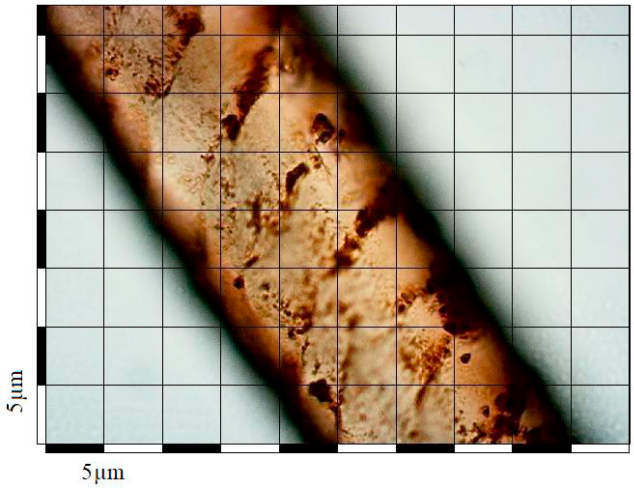
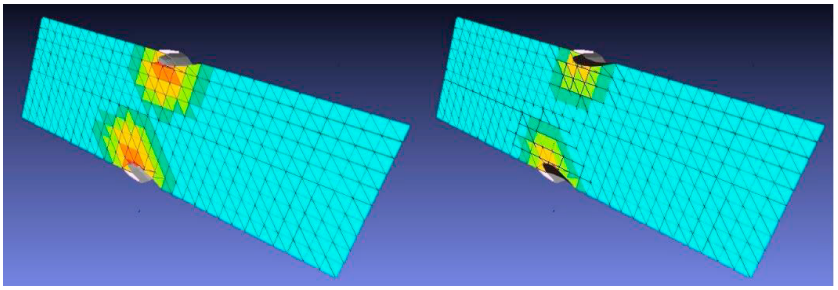


Fig. 2. Textile fiber coated with magnetite.

The incorporation of a nanomagnetic mixture into textile fibers fills potential stress concentrators, thereby increasing their strength. The stress–strain state of the fibers was analyzed using finite element analysis with both two-dimensional and three-dimensional elements, following the approach described by Riabchykov et al. (2018).

A fiber model with natural stress concentrators was subjected to longitudinal loading. The scales located on the fiber surface generate additional stress sources, resulting in elevated internal stresses within the fiber (Fig. 3a). When the mixture of divalent and trivalent iron oxides is applied to the fiber surface, it accumulates in the cavities between the scales, reducing stress concentrations. Consequently, the internal stress level within the fiber is substantially decreased (Fig. 3b).

After conducting a series of experiments to determine the tensile strength of textile fibers, these results were confirmed. A single-yarn tensile strength tester Y001A was used. The specific tensile strength of fibers was determined per unit cross-sectional area.



a b

Fig. 3. Stress in textile fiber (a – natural state, b – fiber coated with magnetite).

Fiber samples with different nanomagnetite contents were prepared. The mixture content was determined as a percentage of the initial fiber mass. The dependence of the change in fiber strength on the magnetite content is shown in Fig. 4.

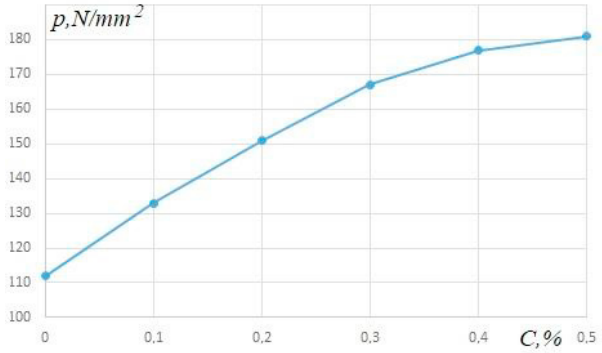


Fig. 4. Change in the strength of textile fibers depending on the magnetite content.

The experimental results demonstrate a significant increase in fiber strength with the addition of magnetite. Initially, the growth occurs very rapidly. In particular, at a nanocomponent content of 0.2%, the strength increase can reach □ 35% compared with fiber strength without magnetite. A magnetite content of 0.4–0.5% enhances the fiber strength by □ 60%.

4. Conclusions

Recent investigations have demonstrated that the incorporation of nanocomponents based on divalent and trivalent iron oxides (Fe^{2+} /Fe^{3+}), particularly magnetite (Fe_3 O_4), represents an effective strategy for enhancing the strength of textile fibers. A synthesis protocol for magnetite and a fiber-coating technique were developed, enabling the uniform distribution of nanoparticles within the fiber cavities and on their surfaces. This uniform dispersion reduced stress concentrations and significantly improved the mechanical performance of the fibers.

Mechanical testing corroborated the modeling results: even a minimal addition of magnetite (0.2–0.5%) resulted in □ 35–60% increase in tensile strength.

The integration of magnetic nanocomponents into textile fiber structures thus opens promising avenues for the development of high-strength, multifunctional materials with potential applications across diverse sectors, including the textile, aerospace, automotive, medical, and defense industries. Future research should prioritize optimizing magnetite concentration, assessing the long-term stability of the coatings, and further expanding the functional capabilities of these advanced fibers.

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