Application of Powder Materials and Functional Coatings
Применение порошковых материалов и функциональных покрытий

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Research article
Научная статья

The influence of magnetic fields on the strength of modified epoxy resin composites

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Abstract. The aerospace industry is currently undergoing a major trend of transitioning to composites. This study exanines the utilization of the magnetic field of rotating dipoles to produce high-strength iron powder-containing composites. The physical and mechanical properties of the modified epoxy composites were investigated through the use of SEM to analyze their microstructure and elemental composition, and a component distribution map was developed for the samples. Results indicate that the application of the magnetic field of rotating dipoles enhances the compression strength by 16.6 % relative to samples that were not exposed to it. Additionally, the magnetic field eliminates gas porosity and cavities formed during stirring. Tests conducted on composites with a higher content of Al particle showed that the magnetic field of rotating dipoles contributes to the release of excess aluminum as a surface layer. The use of the magnetic field of rotating dipoles is a promising technology for producing enhanced composites with superior physical and mechanical properties, which could potentially be used as structural material in aerospace industry or as adsorbing materials in microelectronics.

Keywords: epoxy composite, magnetic field of rotating dipoles (MFRD), compressive strength, filler, iron powder, microstructure

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Исследование влияния магнитных воздействий на прочностные характеристики модифицированных эпоксидных композиционных материалов

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Аннотация. Замена традиционных материалов композиционными представляет собой важный вектор развития авиационной и аэрокосмической отраслей промышленности. В работе рассмотрены вопросы применения магнитного поля вращающихся диполей с целью получения композиционных материалов на основе порошкового железа с высокими прочностными и структурными характеристиками. Исследованы физико-механические свойства модифицированных эпоксидных композиционных материалов. С помощью средств электронной микроскопии исследованы микроструктура, элементный состав и получена карта распределения компонентов в получаемых образцах. Экспериментальным путем выявлено, что при наложении магнитного поля вращающихся диполей прочность при сжатии композитов увеличивается на 16,6 % относительно образцов, полученных без применения этой технологии. Это вызвано тем, что данный метод позволяет удалять возникающую в процессе механосинтеза газовую пористость и раковины во внутренней структуре материала. Серия экспериментов с добавлением увеличенного массового соотношения Al-частиц показала, что магнитное поле вращающихся диполей способствует вытеснению излишков алюминия в виде поверхностного слоя. Таким образом, можно заключить, что применение магнитного поля вращающихся диполей является перспективным направлением в области создания композиционных материалов с улучшенными физико-механическими характеристиками. Получаемые эпоксидные композиты могут быть использованы в качестве конструкционных материалов в авиационной и космической отраслях, а также в качестве материалов адсорберов в радиотехнической аппаратуре и микроэлектронике.

Ключевые слова: эпоксидный композиционный материал, магнитное поле вращающихся диполей (МПВД), прочность на сжатие, наполнитель, порошковое железо, микроструктура

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Introduction

The demand for composite materials filled with powders has been increasing steadily every year, as evidenced global statistics on the polymer market. For example, in 2020, the volum of the global polymer composite market was approximately 13 mln tons [1].

In Russia, the Technet roadmap has been implemented to facilitate the development of advanced manufacturing technologies and composites [2]. The roadmap has identified controlled microstructure composites as one of the key future technologies to be explored.

Thermoplastic polymers and epoxy resins are frequently used as matrices in the production of filler powder-based composites [3]. The composites incorporating thermoplastic polymers are known for their broad mechanical properties and wide-ranging applications [4; 5]. However, it is essential to note that the physical and mechanical characteristics of these composites are not always consistent and may vary.

The incorporation of reinforcing fillers in such composites has been found to enhance the adhesive bond [6; 7] and strength [8]. The dispersion structure of these composites significantly contributes to their strength, primarily through the formation of structured layers [9], filler cluster-aggregation [10], and crystallization [11].

Starokadomsky D. et al. [12] demonstrated the potential for enhancing the strength and durability of epoxy composites by incorporating silicon carbide and titanium nitride fillers. The introduction of these fillers resulted in a significant increase in microhardness (150–200 %) and compressive strength (by 9 %).

Recently, electrophysical methods have been employed to enhance the physical and mechanical characteristics of composites. These methods involve exposing composites to a strong static magnetic field [13; 14], magnetic pulses [15], and the magnetic field of rotating dipoles (MFRD) [16]. MFRD is an efficient technique for regulating the packing structure of powders in composites without requiring significant energy input.

The aim of this study is to investigate the impact of the magnetic field of rotating dipoles on the strength and other structural characteristics of composites containing iron and aluminum powder.

Research methods

Materials

In our study, we examined two types of particles, namely iron microparticles PZHV1.160.26 (GOST 9849-86) and aluminum powder PAP-2 (GOST 5494-95). The matrix used was composed of a mixture of ED-20 dian resin (GOST 10587-84) and polyethylene polyamine (PEPA) in a 5:1 ratio.

Composite manufacturing

Figure 1 illustrates the patented process used to create the modified epoxy composite samples in our study. The experiment involved two types of fillers: powdered iron, and a mixture of powdered iron and Al-particles in a 7:3 weight ratio. The ED-20 resin-based composite was mixed with the powder filler, which contained 70 wt. %. PZHV1.160.26 iron microparticles and 30 wt. %. PAP-2 aluminum powder, in a polymer cylinder with a 20 mm ID. The hardener, PEPA, was then added to the mixture in a quantity equal to 1/5 of the weight of the resin. The resulting compositions were heat treated at a temperature of 90 °C for 1–2 min to eliminate gas porosity, and then poured into molds. Finally, the samples were removed from the molds for analysis.

We fabricated four composite samples with identical dimensions of 20 mm in diameter and 20 mm in length. Among these samples, two were composed of Fe–Al (FAM) and Fe (FM) microparticles and were exposed to the magnetic field generated by rotating dipoles (Figure 2). The induction level of the magnetic field was set to 0.5–0.7 Tesla [17; 18]. The remaining two samples served as refrence samples and were not exposed to the magnetic field.

Strength measurements

We used an IP-100M automatic hydraulic press to apply static loads to the composite samples for both compression and bending tests.

The loading rate was set to 1 mm/min. We then plotted an experimental load-compressive strain curve to estimated the compressive failure stress and relative strain of the samples. To obtain precise measurements, we recorded the compression process at a high frame rate.

The compressive failure stress (σ, MPa) was determined as

$$\sigma = F/A,$$

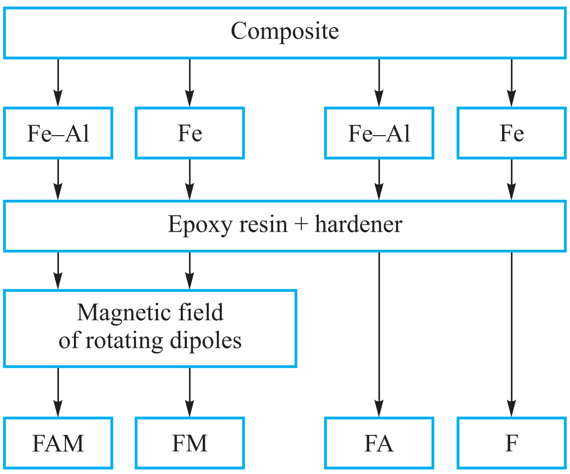

Fig. 1. Composite exposure to the magnetic field of rotating dipoles
FAM – Fe–Al (MFRD); **FM** – Fe (MFRD);
FA – Fe–Al (no MFRD); **F** – Fe (no MFRD)

Рис. 1. Блок-схема получения модифицированных эпоксидных композиционных материалов
FAM – Fe–Al (МПВД); **FM** – Fe (МПВД);
FA – Fe–Al (без МПВД); **F** – Fe (без МПВД)

where F is the max compressive strength, N; A is the cross-section area of the sample, mm^2.

The relative compressive strain at failure was estimated as

$$\varepsilon = \frac{\Delta h}{h_0} \cdot 100~\%,$$

where Δh is the relative strain, mm; h_0 is the initial sample height, mm.

During the test, we closely monitored the samples being tested. After the tests, each sample was photographed for damage analysis.

To examine the microstructure, elemental composition, and component distribution in the composite samples, we employed an EVO HD 15 scanning electron microscope (Carl Zeiss, UK/Germany) in low vacuum (EP, 70 Pa), 20–25 kV.

Results and discussion

Strength properties

We generated experimental load-strain curves for the compocite samples (Figure 3). As the powder-filled composite samples were compressed, the majority of the load was applied to the matrix, which was followed by a sharply decrease in load after matrix destruction. The load-strain curves for the cylindrical samples (Fig. 3) indicate that the volume deformation of composites causes softening, which is more significant for the samples made without MFRD.

The experimental compressive failure stress values are summarized in the table. The composite sample with the Fe–Al filler exposed to MFRD exhibited the highest compressive failure stress value of 57.5 MPa, indicating its superior strength compared to the othe composite samples.

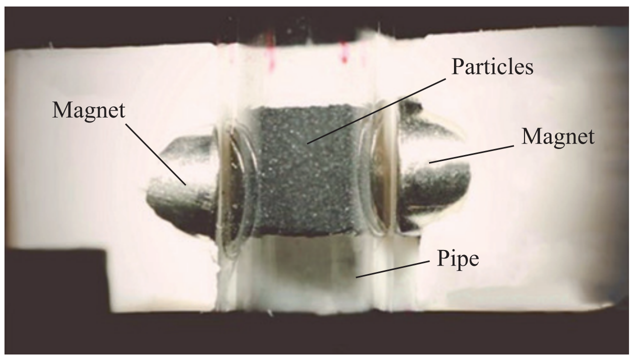

Fig. 2. Modified epoxy resin composite manufacturing process

Рис. 2. Схема воздействия магнитного поля вращающихся диполей на материал

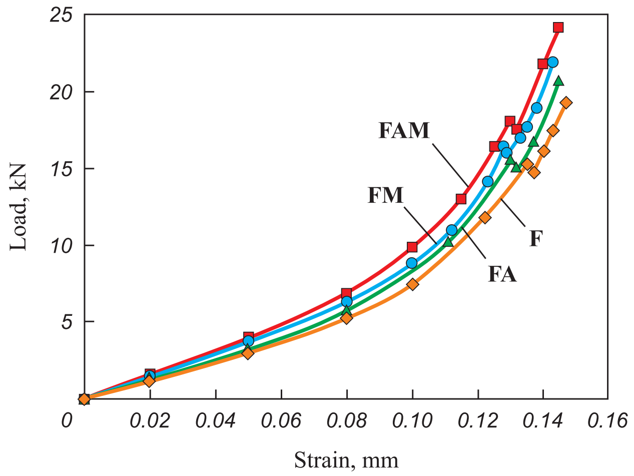

Fig. 3. Strain curves for the composites
FAM – Fe–Al (MFRD); **FM** – Fe (MFRD);
FA – Fe–Al (no MFRD); **F** – Fe (no MFRD)

Рис. 3. Кривые деформирования композиционных материалов, полученных по разным технологиям
FAM – Fe–Al (МПВД); **FM** – Fe (МПВД);
FA – Fe–Al (без МПВД); **F** – Fe (без МПВД)

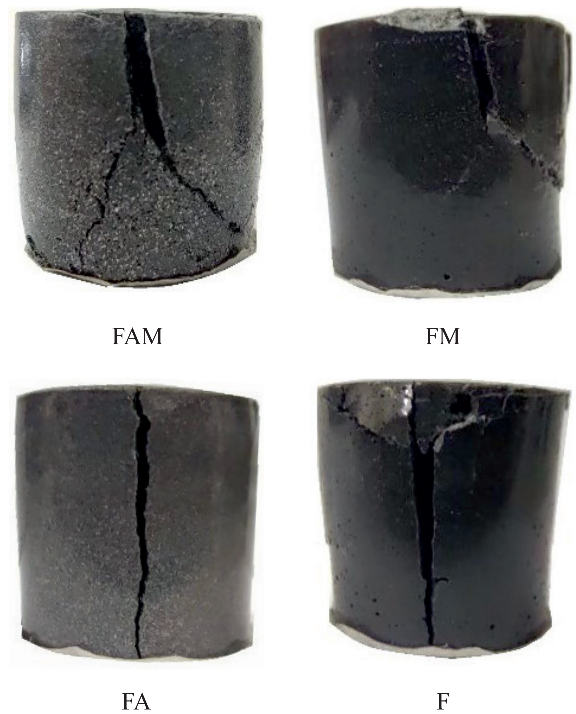

Fig. 4. Samples after the compression test
FAM – Fe–Al (MFRD); **FM** – Fe (MFRD);
FA – Fe–Al (no MFRD); **F** – Fe (no MFRD)

Рис. 4. Фотографии образцов после испытания на сжатие
FAM – Fe–Al (МПВД); **FM** – Fe (МПВД);
FA – Fe–Al (без МПВД); **F** – Fe (без МПВД)

A comparison was made between the mechanical properties of composites that were exposed and not exposed to MFRD. The results showed that the samples exposed to MFRD were able to withstand a greater load due to a denser and structured distribution of particles in the epoxy matrix [19].

The composite strength of the the Fe–Al filler exposed to MFRD was found to be 30 % higher (57.5 MPa) compared to that of the sample containing only epoxy resin (44 MPa). Additionally, the hardness of the samples was increased by 16.6 % due to the effect of MFRD.

Several researchers have noted the reinforcing effect of incorporating a dispersed system into a polymer matrix [20]. For example, the addition of micro silicon has ben shown to improve strength by 10–15 % [21]. The inclusion of silicon nanoparticles has been found to increase the compressive strength of epoxy composites by 30 % [22].

Visual inspection of the samples after compression revealed brittle fracture in both cases (Figure 4). However, the samples exposed to MFRD showed cracks along the sloped planes, whereas the samples not exposed to MFRD had cracks along the straight planes. This difference is likely due to the packing of particles in the polymer matrix, which is supported by the difference in the composite densities (see table).

Microscopic examination and component distribution maps in the composite samples

Figure 5 displays cross-sections of the composites exposed and not exposed to MFRD. The notable difference is the presence of air cavities in the sample made without MFRD.

Compressive mechanical properties of the composites

Механические свойства при сжатии композиционных материалов различного типа

Composite	ρ, g/cm^3	F_{max}, kN	σ, MPa	ε, %
FAM (Fe–Al + MFRD)	2.79	18.06	57.5	0.650
FM (Fe + MFRD)	2.86	16.39	52.2	0.635
FA (Fe–Al no MFRD)	2.72	15.48	49.3	0.650
F (Fe no MFRD)	2.64	15.26	48.6	0.675
Epoxy resin	1.20	13.80	44.0	0.800

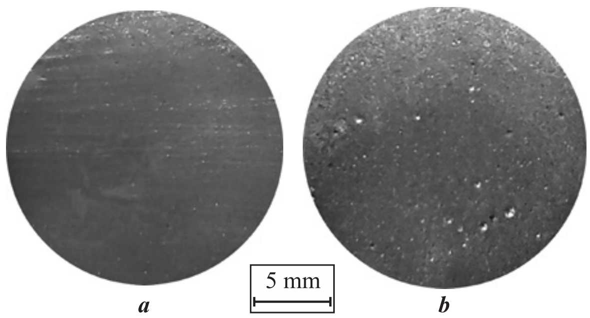

Fig. 5. Surface structure of the FAM (***a***) and FA (***b***) composites

Рис. 5. Структура поверхности композиционных материалов FAM (***a***) и FA (***b***)

To assess the homogeneity of the particle distribution in the composite, component distribution maps for the FA and FAM samples was produced (Figure 6). The results demonstrate that the magnetic field of rotating dipoles produces a more uniform distribution without particle agglomeration.

Conclusion

We tested the compressive strength of cylindrical samples made of epoxy composites containing Fe–Al and Fe particles. It was discovered that the Al-containing sample exposed to MFRD exhibited the highest strength being 14 % greater than that of the sample not exposed to MFRD. The elimination of gas porosity and cavities during the stirring by magnetic degassing is the reason for this phenomenon.

Such composites can be used as structural material in aerospace, or as adsorbing materials in microelectronics.

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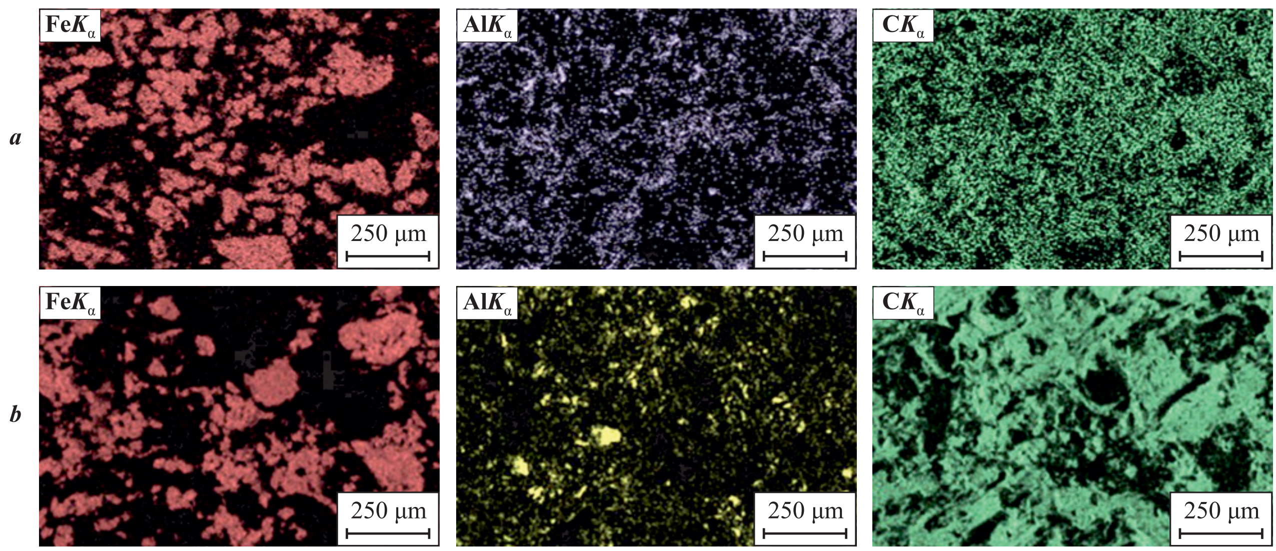

Fig. 6. Fe, Al, and C distribution maps for the FAM (***a***) and FA (***b***) samples composites

Рис. 6. Карты распределения Fe, Al и C в композиционных материалах FAM (***a***) и FA (***б***)

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