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Enhanced Mechanical Properties of Single Carbon Fibres *via* Electromagnetic Treatment: A Comparative Analysis

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Abstract

This study investigates the effect of Electromagnetic Field Treatment (EMFT) on the mechanical properties of Polyacrylonitrile (PAN)-based single carbon fibres, which are critical materials in high-performance composites widely utilised in the aerospace and automotive sectors due to their superior strength and stiffness. Carbon fibres were subjected to controlled electromagnetic field exposure, with both treated and untreated fibres rigorously evaluated through tensile testing. The treated fibres exhibited a notable 6.12% increase in yield strength, along with a substantial improvement in tensile modulus compared to the control samples. Scanning Electron Microscopy (SEM) analysis revealed a smoother surface morphology in the treated fibres, potentially contributing to enhanced flexibility and a reduction in microscale defects. These findings suggest that EMFT may serve as an effective technique for optimising the mechanical performance of carbon fibres, thereby enhancing their suitability for advanced applications.

Keywords: Carbon Fibre Reinforced Polymer (CFRP), Single Carbon Fibre (SCF), SEM, Electromagnetic Field Treatment (EMFT), Polyacrylonitrile (PAN)

Introduction

Polyacrylonitrile (PAN) and pitch based carbon fibres are widely utilised as reinforcements in composite materials, including carbon fibre-reinforced plastics, ceramics, carbon-carbon composites, and carbon fibre-reinforced metals, owing to their high specific strength and modulus [1]. These composites have become predominant in industries such as aerospace, automotive, and sporting goods, where high-performance materials are essential for lightweight structures and improved fuel efficiency [2]. Among carbon fibres, PAN-based fibres, derived from polyacrylonitrile precursors, are the most widely used due to their superior mechanical properties and ease of production [3]. In contrast, pitch-based carbon fibres, derived from petroleum or coal tar pitch, offer advantages in thermal and electrical conductivity, particularly in applications demanding high modulus [4].

The mechanical properties of carbon fibres including strength, modulus, and density are significantly influenced by both the precursor material and the heat treatment process. PAN based fibres typically exhibit high tensile strength and low density (1.75-2.00 g/cm³), while pitch-based fibres provide higher modulus but at the expense of lower strength [5]. Given the critical role that these fibres play in composite performance, precise characterisation of their properties is essential for the efficacy of modelling tools used in predicting the behaviour of composite materials.

Magnetic fields represent a sustainable and non-contact, high-energy physical force with diverse impacts on materials, influencing their thermodynamic and kinetic states during processing. By transferring energy at an atomic level, magnetic fields can significantly affect the migration, alignment, and arrangement of atoms, molecules, ions, and grains within materials [6]. This results in profound alterations to both microstructure and physical properties, allowing for extensive control over material performance, especially in terms of mechanical and structural characteristics.

Since the 1960s, research has shown that magnetic fields can enhance the properties of ferromagnetic materials, prompting exploration of similar effects on non-ferromagnetic materials [7]. As research has progressed, magnetic field-assisted processing techniques, such as electromagnetic stirring, have emerged as valuable methods for refining metal microstructures and properties. These advancements are primarily observed in magnetic field-assisted heat treatments and plastic deformation processes, which have achieved promising results in developing new materials and optimising existing ones [8,9].

This study explores how Electromagnetic Field Treatment (EMFT) affects the mechanical properties and surface morphology of PAN-based carbon fibres, building on earlier findings that suggest EMFT can enhance strength and resistance to delamination [10]. However, the mechanisms behind these improvements remain unclear [11]. By examining microstructural changes, we aim to clarify how EMFT contributes to performance gains in these fibres, which are particularly suited for high-performance applications.

Using tensile testing and SEM analysis, this research assesses EMFT-induced changes in yield strength, ductility, and surface characteristics of PAN-based fibres. We specifically analyse alterations in surface morphology and plastic deformation, linking them to overall gains in strength and flexibility. By identifying these micro-to-macro connections, the study highlights EMFT's potential for optimizing materials in demanding applications, such as aero-structural composites, where enhanced mechanical properties are critical (Figure 1).

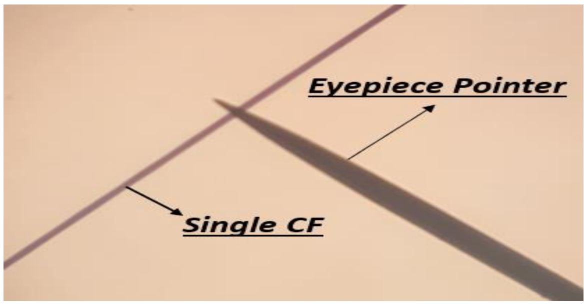

Figure 1: Verification of a single carbon fibre presence and lack of defects with optical microscope.

Materials and Methods

Polyacrylonitrile (PAN)-based Single Carbon Fibres

Polyacrylonitrile (PAN)-based carbon fibres, CF-TOW-3K with a diameter of 7 µm, were sourced from Easy Composites Ltd.

Specimen preparation

A single carbon fiber was carefully extracted from a 3K carbon fiber tow and secured to a cardboard base using a quick-setting adhesive. The fiber was then examined under an optical microscope (motic) at 10X magnification with a 0.25 numerical aperture, as shown in Figure 1, to confirm the use of an intact single fiber for all specimens and check for defects or breakage. The cardboard base was prepared following British Standard ISO 11566:1996 specifications, shown in Figure 2. After detailed inspection, the specimens were prepared for treatment and testing.

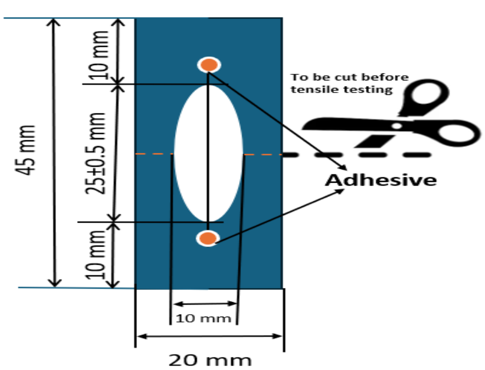

Figure 2: Securing a single carbon fibre on a mounting holder.

EMF detector

An Electromagnetic Field (EMF) detector (Naroote2gr3cst4wb) was employed to measure the intensity of electromagnetic fields generated by electrically charged objects during the experiment. EMF detectors, commonly used in fields such as electrical engineering, industrial maintenance, and environmental monitoring, provide measurements of electromagnetic radiation, typically in volts per metre (V/m) for electric fields or in Tesla (T) for magnetic fields.

Electromagnetic Field Treatment (EMFT)

An electromagnetic field generator, specifically designed to produce the required frequency and amplitude, was developed for the treatment of the specimens. This generator allowed for adjustable settings to accommodate different electromagnetic field strengths. The samples were exposed to an electromagnetic field for 15 minutes at room temperature, placed between two generators operating at a field strength of 0.05 Tesla, as shown in Figure 3. Although exposure durations of 5, 10, 15, 30, and 60 minutes were initially tested, 15 minutes was selected as the optimal treatment time due to its effectiveness and efficiency.

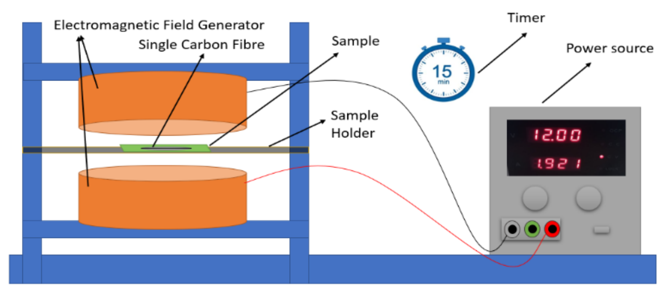

Figure 3: Schematic view of the EMF Treatment of Single CF.

Tensile testing

Tensile tests were conducted in accordance with the BS ISO 11566:1996 standard at room temperature (21 ± 3 °C) and relative humidity (50 ± 5%). Both treated and untreated fibres, each with a thickness of 7 µm (Easy Composites Ltd data sheet), were subjected to tensile testing using a 100 N load cell on an Instron Universal Testing Machine (Model 3369- K3175), operating at a crosshead speed of 0.05 mm/min. The gauge length was set at 25 mm, with the cross-sectional area calculated as 3.8465E-05 mm². A total of twenty specimens were tested, comprising ten treated and ten untreated fibres (Figure 4).

Figure 4: Tensile testing a single carbon fibre with modified top grip.

Scanning Electron Microscope (SEM)

A Scanning Electron Microscope (Hitachi S-3400 N) was employed to analyse the surface morphology of both treated and untreated carbon fibre samples. Due to the conductive nature of carbon fibres, no gold coating was necessary for imaging, as electrons could pass through directly. Carbon tape was applied to a 45° holder to secure the samples, allowing for optimal angled views for comparison. Multiple accelerating voltages were tested, with the clearest images captured at 2 kV and a 5-micrometer scale, as shown in Fig. 7.a & 7.b.

Result and Discussion

Instron 3369-K3175 mechanical testing

Figure 5a, illustrates the average failure strain percentages for untreated (UTS) and treated (TS) carbon fiber samples. The untreated fibres exhibit an average failure strain of 1.37%, whereas the treated samples show a slight increase to 1.48%. This difference suggests that electromagnetic field treatment may enhance the ductility of the carbon fibres, allowing them to withstand greater strain before failure. The error bars highlight the variability within each sample group, supporting the observed trend of improved strain capacity in the treated samples.

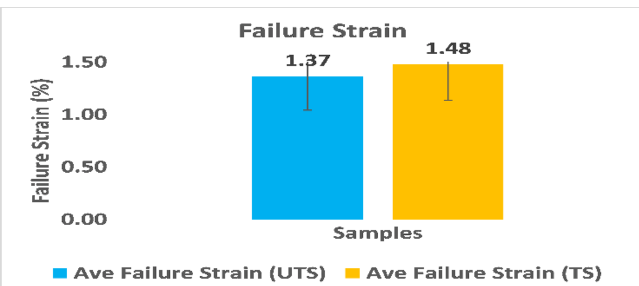

Figure 5a: Tensile result for treated and untreated samples.

Figure 5b, illustrates the yield strength of untreated (UTS) and treated (TS) carbon fiber samples, with the average yield strengths at 4958.27 MPa for UTS and 5261.56 MPa for TS. The yield strength was measured as the offset yield stress at 0.2%, meaning that the stress at which the material exhibits a permanent strain of 0.2% was taken as the yield point. This offset method allows for a standardized way to determine the yield strength, particularly in materials where a clear yield point is not evident. The Treated Sample (TS) shows a slight increase in yield strength compared to the untreated sample, indicating a potential enhancement in mechanical properties due to treatment.

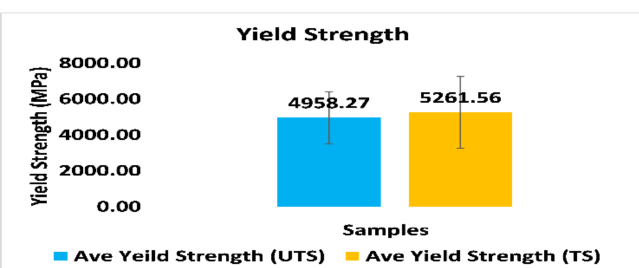

Figure 5b: Tensile results for treated and untreated samples.

In Figure 5c, the tensile modulus values for untreated (UTS) and treated (TS) carbon fiber samples are presented. The untreated sample exhibits an average tensile modulus of 3.69 GPa, while the treated sample shows a slightly higher average of 3.75 GPa. This minor increase in tensile modulus after treatment suggests a potential enhancement in stiffness, though the difference is not substantial. The error bars indicate a similar range of variability for both samples, suggesting consistent results across specimens within each category. Overall, the electromagnetic treatment appears to have a minimal effect on tensile modulus, as the values for treated and untreated samples are nearly comparable.

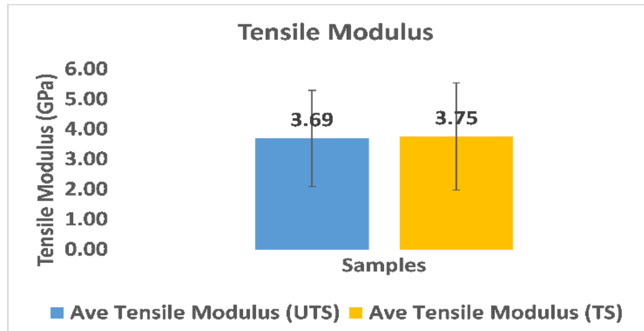

Figure 5c: Tensile results for treated and untreated samples.

Figure 6 shows the relationship between yield strength and strain for both treated and untreated specimens during tensile testing. The results clearly demonstrate that the treated samples exhibit superior mechanical properties compared to the untreated ones. Specifically, the treated specimens showed a significant increase in yield strength, indicating an enhanced resistance to deformation under applied stress. This improvement suggests that EMFT has modified the microstructure of the fibres, resulting in a stronger material. The treated specimens endured higher stress before reaching the yield point, making them more resistant to permanent deformation.

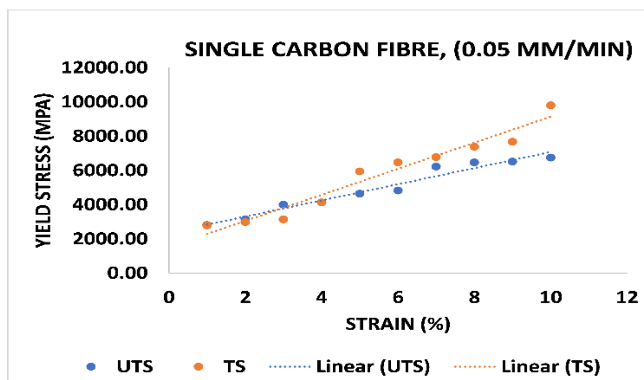

Figure 6: Tensile results for treated and untreated samples.

In addition to increased yield strength, the treated specimens demonstrated enhanced plasticity, reflected by an expanded range of plastic deformation. This improvement in ductility suggests that the treated materials can absorb greater energy under tensile loads without failure. The combined enhancements in yield strength and plasticity underscore the efficacy of Electromagnetic Field Treatment (EMFT) in enhancing the mechanical performance of PAN-based carbon fibres, making them even more suitable for demanding applications in aerospace and automotive industries.

Scanning Electron Microscope (SEM)

SEM imaging revealed clear microstructural distinctions between the treated and untreated specimens. Untreated fibres exhibited sharper edges and angular surfaces, characteristic of a rigid, brittle morphology. In contrast, treated fibres displayed smoother surfaces and rounded edges, suggesting a reduction in surface irregularities due to Electromagnetic Field Treatment (EMFT). This smoother morphology likely enhances flexibility and ductility, as reducing sharp, stress-concentrating features may promote more uniform deformation of the fibres under applied loads. The SEM image of the untreated specimen, with its more angular and abrupt fibre cuts, suggests a lack of uniformity that could lead to localised failure points under stress. In comparison, the smoother profile of the treated fibres indicates a more homogeneous material response, potentially reducing the likelihood of premature failure.

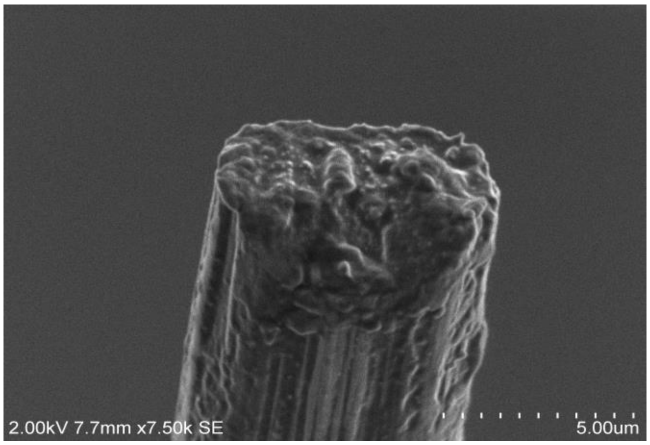

Figure 7a: SEM view for treated sample at 2kv, 5μm.

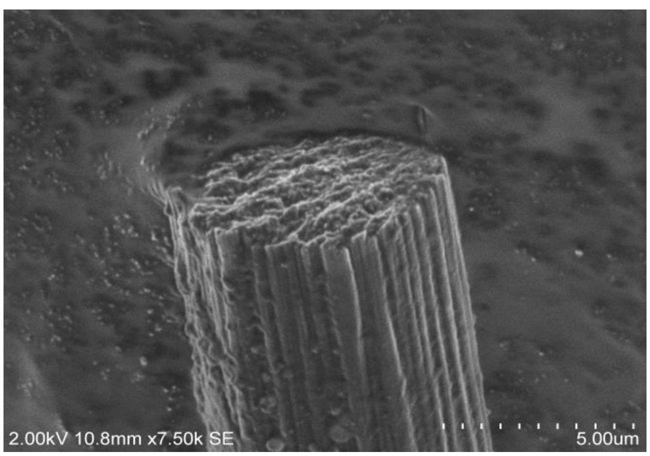

Figure 7b: SEM view for untreated sample at 2 kv,5μm.

Conclusions

This study has demonstrated the potential of Electromagnetic Field Treatment (EMFT) to enhance the mechanical properties of PAN-based single carbon fibres significantly. Comparative analysis of treated and untreated fibres revealed that EMFT-treated fibres exhibit a 6.12% increase in yield strength, improved failure strength, and a higher tensile modulus, reflecting an enhanced capacity to resist deformation and withstand tensile forces.

Additionally, Scanning Electron Microscopy (SEM) analysis showed morphological changes, with treated fibres displaying smoother edges and surfaces compared to the untreated samples. This suggests that EMFT not only strengthens the fibres but may also contribute to improved flexibility and a reduction in microscale defects.

While these results underscore the effectiveness of EMFT in improving the mechanical performance of PAN-based carbon fibres, further research is needed to clarify the mechanisms responsible for these enhancements. Future studies should investigate the long-term effects of EMFT, especially for high-performance applications such as aerospace and automotive sectors.

Acknowledgement

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