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EVALUATION OF COPPERHYDROXYAPATITE ADDITIVE ON FEMTOSECOND LASER ABLATION OF CARBON FIBER REINFORCED PLASTICS

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Abstract: Carbon fiber reinforced plastics (CFRP) are widely used in aerospace, automotive, and marine industries due to their excellent strength-to-weight ratio, chemical resistance, and formability. However, their heterogeneous structure complicates conventional machining, often requiring multistep processing. Laser micromachining, particularly with femtosecond (fs) pulses, offers a promising alternative by minimizing heat-affected zones (HAZ) and enabling precise ablation. Yet, uneven ablation between the epoxy matrix and carbon fibers remains a challenge. In this work, copper-substituted hydroxyapatite (Cu-HAp) microparticles were synthesized and introduced into the epoxy matrix to improve laser energy absorption and ablation uniformity. SEM analysis revealed that Cu-HAp particles possess a hierarchical quasi-cubic morphology with a high surface area, favorable for infrared absorption. CFRP samples modified with Cu-HAp were processed using a 1030 nm fs-laser, and the resulting surface morphology was examined. Compared to unmodified systems, Cu-HAp-modified composites showed more defined ablation zones, deeper material removal, and enhanced uniformity across fiber and matrix phases. The results confirm that Cu-HAp serves as an efficient near-infrared absorber, enhancing the precision and quality of fs-laser machining of CFRP. These findings support the potential of Cu-HAp additives for advanced micromachining and functional surface structuring of polymer composites.

Key words: CFRP, femtosecond laser, copper hydroxyapatite, epoxy resin, carbon fiber.

Carbon fiber reinforced plastics (CFRP) have a number of properties that provide them with applications in aerospace, automotive and marine applications, including lightness, strength, ease of formation, ease of scaling, and resistance to aggressive environments. However, the processing of such material has difficulties due to the heterogeneity of phases (fiber and polymer), which requires an increase in processing operations [1]. One of the promising processing methods is laser processing, however, for CFRP there is a problem related to heat affected zones (HAZ) [2]. The laser processing method utilizes constant or pulsed laser exposure, but this method is energy intensive and the cut site has a high HAZ value [3].

The use of femtosecond laser pulse can reduce the influence of HAZ due to high machining accuracy and minimizing the heating area of the material [4]. Another advantage of femtosecond laser processing is the possibility of equalizing the ablation rate for both the polymer part (epoxy matrix) and reinforcing fibers (carbon fiber) in the composite material. The epoxy degrades much faster than the carbon fiber when exposed to the laser beam, resulting in uneven cutting of the CFRP. One option to further improve the thermal resistance of the resin is to introduce adsorbers - additives that will sorb the laser radiation and compensate for the heating. Copper hydroxyphosphates have attracted attention due to their strong absorption in the NIR region and are a possible adsorber for systems with laser radiation with a wavelength of 1030 nm [5]. The aim of this work was to determine the effect of copper hydroxyapatite-based additives on the femtosecond laser ablation process.

The synthesis of copper hydroxyapatite particles was performed in accordance with [6]. The surface morphology of synthesized copper hydroxyapatite (Cu-HAp) microparticles was investigated by scanning electron microscopy (Fig. 1). The particles have a well-defined quasi-cubic morphology with well-defined faceted surfaces. The average particle size is 2.5 μm and individual particles consisted of densely packed plate-like substructures. The particles are not agglomerated. Hierarchical and layered surface structure, along with high apparent surface area, which may contribute to more efficient heat dissipation and localized energy absorption during femtosecond laser ablation. These morphological features are expected to enhance the functional performance of the material as an infrared radiation absorber. The hierarchical and layered surface structure, along with the high apparent surface area, may improve the interaction with near-infrared laser radiation, particularly at a wavelength of 1030 nm. Copper-containing hydroxyapatites are known for their strong NIR absorption, and the morphological characteristics observed here may contribute to more efficient heat dissipation and localized energy absorption during femtosecond laser ablation. This supports the potential application of Cu-HAp as an additive for laser-sensitive polymer systems, where precise control over ablation efficiency and thermal effects is critical.

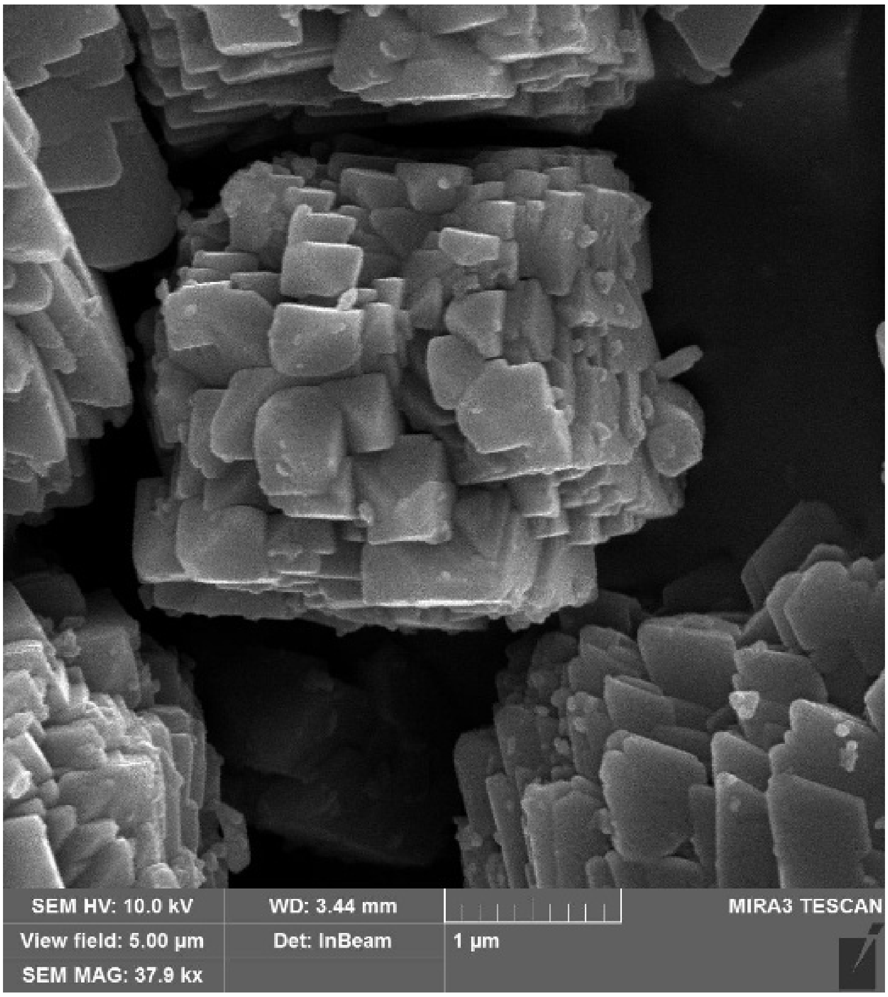

Fig. 1. SEM image of copper hydroxyapatite microparticles

For laser treatment of CFRP, a femtosecond laser-based system was used (Fig. 2). A laser with a wavelength of 1030 nm, forming a Gaussian beam with a diameter of 4,1 mm (at an intensity level of $1/e^2$), was used as a radiation source. The maximum output power of the laser was 6 W, and the operating frequency was up to

200 kHz. The power was adjusted using an external attenuator including a half-wave plate (HWP) and a polarizer (Pol). To convert linear polarization to circular polarization, the beam was additionally passed through a quarter-wave plate (QWP). The beam was focused using a 10x Mitutoyo Plan Apo NIR lens mounted on the Z-axis, with a focal spot diameter of about 3,9 μm ($1/e^2$ level). The CFRP samples were placed on precision XY line tables (Aerotech ANT130-XY). Processing was performed by passing reciprocating the sample to ensure ablation of a 0,5x0,5 mm area. The track spacing was 2,5 μm and the degree of overlap was varied to achieve the optimal value. CFRP samples were washed in an ultrasonic bath in distilled water after processing.

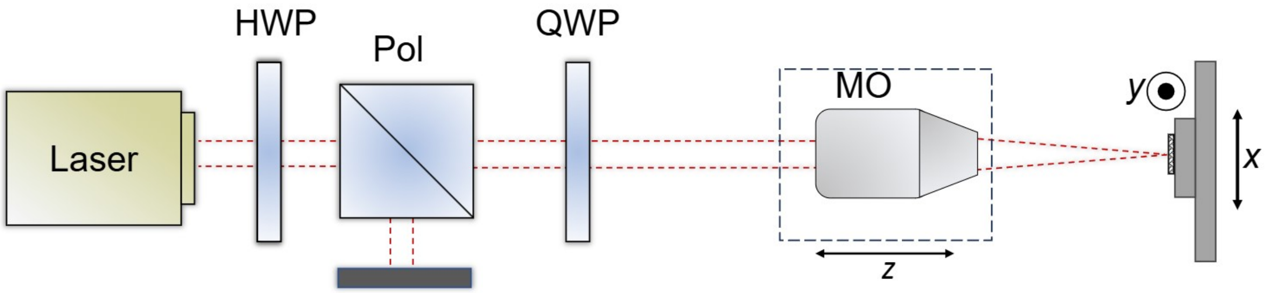

Fig. 2. Optical setup for the fabrication of the CFRP

To evaluate the effect of Cu-HAp additive on the laser ablation performance of CFRP, the surface morphology after exposure to femtosecond laser irradiation was examined by SEM (Fig. 3). The intact epoxy sample (Fig. 3a) exhibits a relatively smooth ablated surface with moderate edge definition, indicating limited NIR laser energy absorption and inefficient material removal. In contrast, the Cu-HAp modified epoxy resin (Fig. 3b, 3c) exhibits a markedly different morphology: the ablation zone appears more textured and granular, with improved material removal and sharper edges. This suggests improved laser absorption in the presence of Cu-HAp, probably due to its strong interaction with near-infrared light, resulting in increased localized heating and effective ablation. Further improvement is observed in fiber-reinforced systems. CFRP (Fig. 3d) shows partial exposure of fibers and a characteristic furrowed texture along the scanning direction, with resin not completely removed. After Cu-HAp modification (Fig. 3e, 3f), the ablation becomes much more uniform. Secondary (SE) and backscattered (BSE) images show improved ablation contrast, indicating deeper penetration into the resin matrix and improved edge quality.

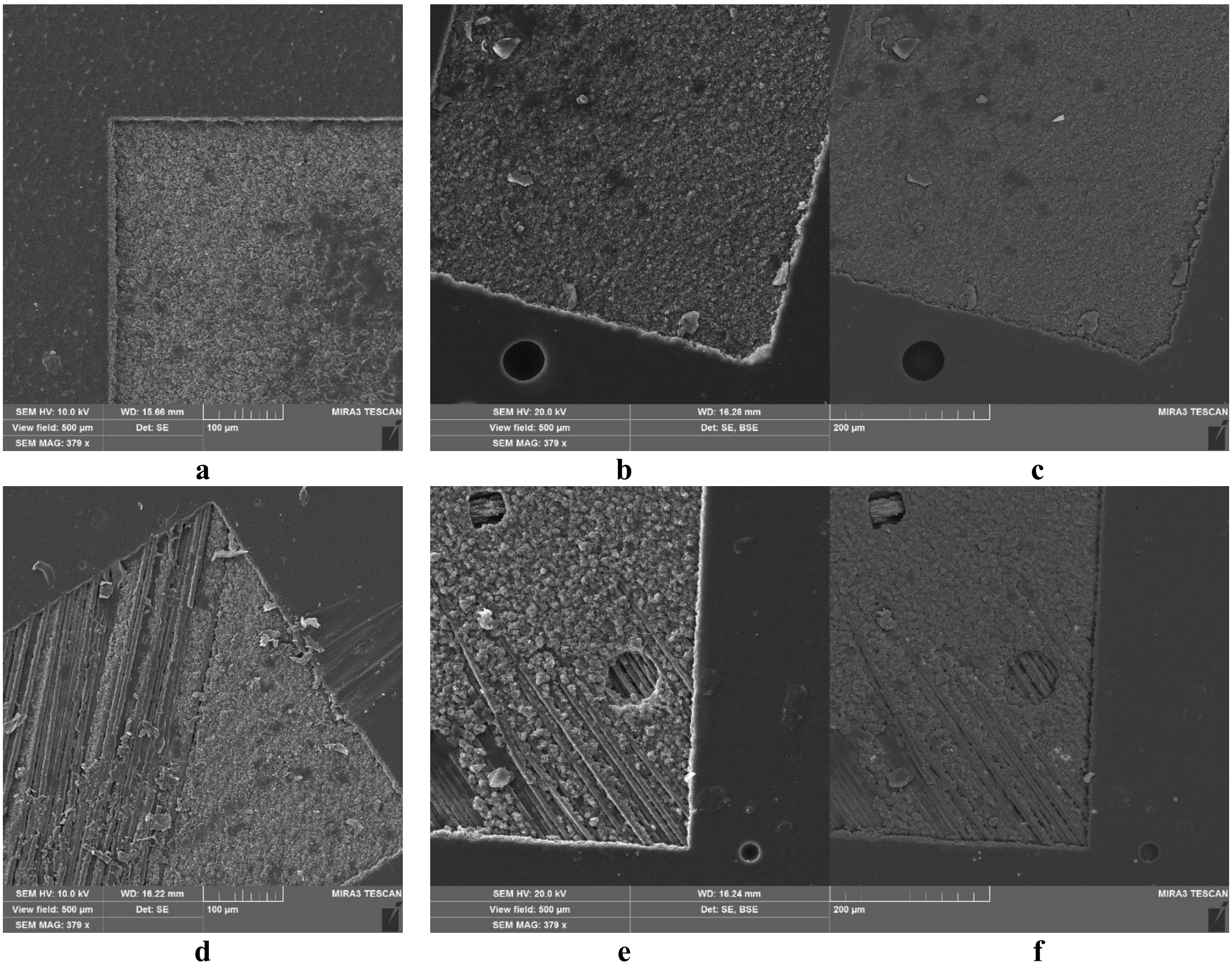

Fig. 3. SEM images: a – epoxy resin; b, c – SE, BSE image of Cu-HAp modified epoxy resin; d – epoxy resin + carbon fiber; e, f – SE, BSE image of Cu-HAp modified epoxy resin + carbon fiber

CONCLUSIONS

The results show that Cu-HAp acts as an efficient absorber of 1030 nm laser radiation, facilitating more controlled and efficient femtosecond laser ablation. This is particularly relevant for applications requiring precise microstructuring and laser cutting of polymer composites.

FUNDING

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ОЦІНКА ВПЛИВУ ДОБАВКИ МІДНОГО ГІДРОКСИАПАТИТУ НА ФЕМТОСЕКУНДНУ ЛАЗЕРНУ АБЛЯЦІЮ АРМОВАНИХ ВУГЛЕЦЕВИМ ВОЛОКНОМ ПЛАСТИКІВ

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Анотація: *Армовані вуглепластики (CFRP) широко використовуються в аерокосмічній, автомобільній та морській промисловості завдяки їхньому відмінному співвідношенню міцності до ваги, хімічній стійкості та здатності до формування. Однак їх неоднорідна структура ускладнює звичайну механічну обробку, часто вимагаючи багатоетапної обробки. Лазерна мікрообробка, особливо з використанням фемтосекундних (фс) імпульсів, пропонує багатообіцяючу альтернативу, мінімізуючи зони термічного впливу (ЗТВ) і забезпечуючи точну абляцію. Проте нерівномірність абляції між епоксидною матрицею і вуглецевими волокнами залишається проблемою. У цій роботі було синтезовано мікрочастинки заміщеного міддю гідроксиапатиту (Cu-HAp) та введено в епоксидну матрицю для покращення поглинання лазерної енергії та рівномірності абляції. Аналіз за допомогою РЕМ показав, що частинки Cu-HAp мають ієрархічну квазікубічну морфологію з високою площею поверхні, сприятливою для поглинання інфрачервоного випромінювання. Зразки вуглепластику, модифіковані Cu-HAp, обробляли за допомогою fs-лазера з довжиною хвилі 1030 нм і досліджували морфологію поверхні, що утворилася. Порівняно з немодифікованими системами, композити, модифіковані Cu-HAp, показали більш чітко окреслені зони абляції, глибше видалення матеріалу та покращену однорідність між волокнистою та матричною фазами. Результати підтверджують, що Cu-HAp слугує ефективним поглиначем ближнього інфрачервоного випромінювання, підвищуючи точність та якість лазерної обробки вуглепластику. Ці результати підтверджують потенціал добавок Cu-HAp для вдосконаленої мікрообробки та функціонального структурування поверхні полімерних композитів.*

Ключові слова: *армовані вуглецевим волокном пластики, фемтосекундний лазер, гідроксиапатит міді, епоксидна смола, вуглецеве волокно.*