Development of Technology for the Production of a New Lightweight Composite Using Recycled Aluminum and Mineralized Wood Waste

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Keywords: Composite Materials, Lightweight Structures, Recycled Aluminum.

Abstract: This paper presents the development of an innovative technology for producing a lightweight composite material utilizing recycled aluminum and mineralized wood waste. The primary objective is to create an environmentally sustainable material that offers significant weight reduction and enhanced mechanical properties for various industrial applications. The process involves the amalgamation of aluminum, reclaimed from post-consumer products, with wood waste that has undergone mineralization to improve its durability and compatibility with metal matrices. Key aspects of the development include optimizing the mineralization process, ensuring uniform dispersion of wood particles within the aluminum matrix, and achieving strong interfacial bonding. Preliminary results demonstrate that the new composite exhibits superior strength-to-weight ratios and thermal stability compared to traditional materials. This advancement holds potential for widespread applications in automotive, aerospace, and construction industries, promoting both resource efficiency and environmental conservation.

1 INTRODUCTION

The management of waste and by-products from manufacturing and agricultural activities represents a great challenge for the circular economy and sustainable development.

The European Commission adopted the new Circular Economy Action Plan (CEAP) in March 2020 (European Commission, 2020) as part of the European Green Deal to improve the benefits of the circular economy on carbon reduction and carbon removals, also through long term storage in wood construction and re-use and storage of carbon in products such as mineralization in building material. While specific regulations regarding the reuse of wood waste from agricultural activities are not explicitly outlined, the European Green Deal emphasizes sustainability, circularity, and resource efficiency across various sectors, including agriculture and forestry. Initiatives and policies aim to reduce waste, enhance resilience, and promote sustainable practices throughout the entire lifecycle of products (European Commission, 2020).

The Republic of Uzbekistan is reforming its legislation to have a sustainable wastes management. The State Committee on Ecology and Environmental Protection of the Republic of Uzbekistan organized in 2019 a roundtable discussion on the “Strategy for solid waste management in the Republic of Uzbekistan for 2019-2028” (State Committee on Ecology and Environmental Protection of the Republic of Uzbekistan, 2019), which promoted, among other topics, the secondary resource utilization, encompassing both reusing and recycling

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Pagliolico, S. L., Turakhujaeva, S., Ubertalli, G., Parmonov, A. and Safarova, M.
Development of Technology for the Production of a New Lightweight Composite Using Recycled Aluminum and Mineralized Wood Waste.
DOI: 10.5220/0014043500004738

In *Proceedings of the 4th International Conference on Research of Agricultural and Food Technologies (I-CRAFT 2024)*, pages 40-44
ISBN: 978-989-758-773-3; ISSN: 3051-7710

of materials, with the aim of an overall energy savings and energy reduction to create new items, and recovery using wastes as alternative energy sources (State Committee on Ecology and Environmental Protection of the Republic of Uzbekistan, 2019).

In the hierarchy of sustainable waste management, waste reduction or minimization comes first. When we reduce waste, we consume fewer raw materials, helping to preserve natural resources. In the central part of the pyramid which represents the hierarchy of sustainable waste management we find recycling, i.e. the processing of waste materials to create new products. This can reduce the energy needed to create new items and conserve raw materials, avoiding waste disposal in landfill. Energy recovery is a step lower and allows to generate energy and reduce the use of landfills. At the base of the pyramid we find landfill disposal, which involves a significant use of land and the risk of methane emissions and leachate formation. The best approach involves a combination of these strategies, prioritizing waste reduction and promoting a circular economy.

Wood waste is commonly either downcycled for use as biomass fuel or upcycled into engineered wood products that exhibit superior properties compared to solid wood. These products are typically created by bonding fragmented wood using organic thermosetting adhesives, including plywood, OSB (oriented strand board), MDP (medium-density particleboard), MDF (medium-density fiberboard), and HDF (high-density fiberboard) (Bianco et al., 2021).

Mineralized wood (MW) can be derived from woodworking waste. One of the authors of this study utilized wood chips, mineralized with spherical, silicon-rich, aluminosilicate particles, as coarse aggregate to create an innovative structural lightweight concrete specifically designed for insulated lightweight building envelope applications, as discussed by (Becchio et al., 2009). Several benefits were achieved, including improved durability, as silica reinforces cell walls, making them more resistant to decay, increased fire resistance, as silica could be a protective layer reducing wood flammability, enhanced strength, due to the impregnation process strengthening the wood structure, and reduced swelling and shrinkage in damp conditions.

One crucial focus within engineering materials science involves developing novel, efficient, and promising alloys for use in foundry production. The utilization of wood waste from agricultural activities, sawmills, and processing industries (which produce panels, building components, and furniture) presents an innovative opportunity for creating lightweight aluminum components reinforced with natural wood fibers. Omoniyi et al. (2022) created aluminum and wood composites by incorporating wood particles into the aluminum alloy matrix using the stir casting technique. These aluminum-based wood composites offer solutions for structural challenges in large roof and floor spans. Characterization results indicate that increasing the wood particle content in the composition, up to a certain percentage in weight, leads to reduced composite density while enhancing impact strength and tensile strength compared to unreinforced aluminum alloys.

In a prior study (Ubertalli et al., 2023), the authors of this research started to explore the feasibility of creating aluminum-mineralized wood (AMW) composites materials as the core for lightweight aluminum components by incorporating mineralized wood chips into an aluminum alloy matrix using a casting process.

Aluminum alloys are the second most used metallic alloys in buildings (skirting, roof, cladding, window and door frame, solar panel, staircase, air conditioning system, heat exchange system, furniture, curtain wall) and constructions (consumer electronic, power line, thermal and electrical engine, spacecraft component, component of land and sea vehicle) thanks to their low density, high ductility and specific strength, higher corrosion resistance than plain carbon steels in environmental atmospheric conditions, and could be 100% recycled, thus reducing the environmental footprint and ecological impact. Furthermore, aluminum is considered non-combustible (A1-Euroclass reaction to fire) because it does not sustain combustion. Some recent research works proposed the use of aluminum foams to produce core cavity in stiffer cast products for automotive and aerospace, with increased stiffness, damping properties, vibration absorption, and acoustic and thermal insulation characteristics, even if the wide pore size distribution and the non-homogeneous localization of pores in the component cause anisotropy in material properties (Ubertalli & Ferraris, 2020; Ubertalli et al., 2020; Ferraris et al., 2021; Ferraris et al., 2022).

In this research it is crucial to focus on improving the efficiency of component materials (Turakhujaeva et al., 2023). Additionally, we investigated the macro and microstructure of the composite samples. Aluminum alloy components are manufactured using sand casting process. Sand casting is one of the oldest and most popular methods that allowing for the production of small batches. The process involves pouring liquid aluminum alloy into sand molds that contain Mineralized Wood (MW) chips inside cylindrical permeable cages, which serve as the core volume inside the component. The liquid aluminum infiltrates the spaces between the wood chips resulting, after solidification, in a continuous, interconnected metal structure, connected to the aluminum skin of the component.

This approach may allow the production of thick-walled components with superior bending and torsional properties compared to thin-walled, ribbed components, while still maintaining a lower overall density. The characterization of the micro and macro structure of Aluminum Mineralized Wood (AMW) composites involved techniques such as optical and electron scanning microscopy and CT-scan. In an ongoing works we will explore how the inclusion of mineralized wood chips impacts the properties of the samples, including vibration and sound absorption (Cottone et al., 2023; Tursunbaev et al., 2023; Tursunbaev et al., 2024).

2 MATERIALS AND METHODS

Four samples have been prepared. Mineralized Wood (MW) chips were selected based on two different size distribution, fine and coarse (Figure 1), oven dried at 103°C until a constant mass was reached, weighed and proportioned for each sample as reported in the Table 1.

Table 1: MW weight and weight percent of coarse and fine chips used in the AMW composite samples (#).

Sample ID	MW_{wtg}	Coarse MW_{wt} %	Fine MW_{wt} %
1	3.18	79%	21%
2	3.16	62%	38%
3	3.27	55%	45%
4	3.55	40%	60%

In Figure 2 are reported the SEM micrographs of the spherical, silicon-rich, aluminosilicate particles formed in mineralization process (a) and the associated EDS spectra (b). These particles have a slight variation in Al, Si and O proportions and significantly differ in size. The morphology and elemental analysis indicated that the particles were composed of aluminosilicate spheres and probably traces of iron.

The micrographs of wood (c) associated with the EDS spectra (d) highlights the morphology of the long tubular wood cells and the deposition on wood cell walls of spherical, silicon-rich, aluminosilicate particles. EDS analysis on wood walls showed the presence of carbon and oxygen, which are the main elements in wood, and, possibly, also the impregnation of the walls by silicon-rich compounds.

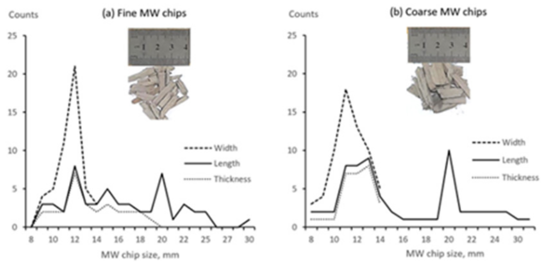

Figure 1: Mineralized wood chips: particle size distribution (length, width and thickness) of fine (a), and coarse chips (b).

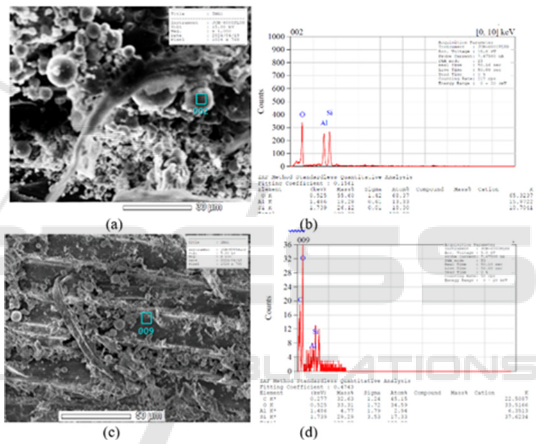

Figure 2: Micrographs of MW chips: SEM image (x1000) (a) and EDS elemental spectra of the spherical, silicon rich, aluminosilicate particles (b); SEM image (x600) (c) and EDS elemental spectra of wood (d).

The recycled aluminum alloy used for casting is the AK5M2, according to the GOST designation (GOST 1583-93, 1993) Tursunbaev et al., 2023; Ubertalli and Ferraris, 2020; Ubertalli et al., 2023). It is a foundry alloy of the system Al-Si-Cu used to manufacture shaped castings by various casting techniques, including sand casting, and having the chemical composition reported in table 2.

Table 2: Chemical composition of samples.

Standard	Si	Cu	Fe	Ti	Al
GOST 1583-93	4-6	1.5-3.5	≤1	0.05-0.2	Rest

Four permeable cylindrical aluminum mesh cages (Figure 3a) containing the MW chips have been placed inside the molds (Figure 3b). Sand molds are formed by packing sand around a pattern, which replicates the external shape of the desired cylindrical casting. These cages formed the core of AMW samples (Figure 3c). Molten AK5M2 alloy is heated up to 750 °C, and it is than poured into the molds containing mineralized wood chips (Figure 3c).

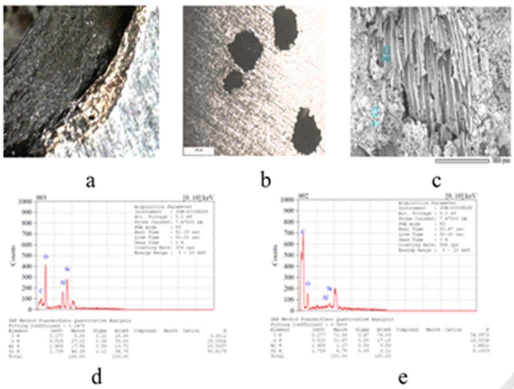

Figure 3: Permeable cylindrical aluminum mesh cages containing the MW chips (a); cylindrical aluminum mesh cages containing the MW chips are placed inside the molds (b); pouring of aluminum into the mold (c).

3 RESULTS AND DISCUSSION

After solidification, the axial section of the samples showed that the mineralized wood chip had become black in color (Fig. 4a) undergoing a pyrolysis process with marked development of fume (observed during casting) and that the aluminum metal cage had melted, allowing to charred wood to float on liquid aluminum. The interface between wood and aluminum appears to copy the shape of the chips, but there is an almost continuous gap between the two materials, also due to the poor wettability of the wood. In the metallographic image of a cross-section (Figure 4b) some bubble-like cavities and nodule-like particles appear. We can assume that they have been generated by bubble gas developed during casting (cf. Figure 5a).

The morphology and the elemental composition of spherical aluminosilicate particles (Figure 4c and Figure 4d) seems not to be changed after casting. On the contrary, the composition of wood (Figure 4c and Figure 4e) varied sensibly (cf. Figure 2d and Figure 4e) because of wood pyrolysis in contact with the molten alloy at high temperature and burning of wood in contact with air. The elemental analysis highlights that the percentage of oxygen is noticeably decreased.

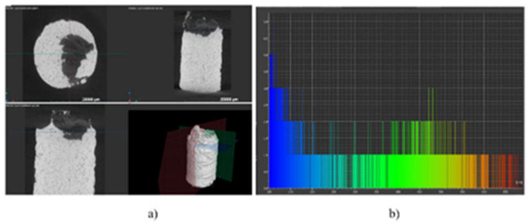

Figure 4: Sample 1 after casting: macro image (a); metallographic image (b); SEM image of MW surface after casting (c); EDS analysis of spherical aluminosilicate particles; EDS analysis of MW after casting (e).

Sample 1 was analyzed by CT-scan showed wood chips on top of the sample, due to the dissolution of the aluminum cage containing the MW chips, the difference of density between metal and wood and the gases developed from wood during casting which did not allow the rapid formation of a skin of solid aluminum on the top of the sample (Figure 5a). It is also evident the high amount of pores and nodule-like particles in the aluminum-based matrix (Figure 5b) due to the delivering of gases before solidification. Gases are produced during partial combustion but mainly wood pyrolysis of the chips wood at high temperature due to hot liquid aluminum.

Figure 5b shows the size distribution of AMW composite void and/or nodule-like particles calculated by the add-on Foam/powder analysis module of CT-scan VGStudio Max 3.5 software (Volume Graphics, Heidelberg, Germany). The void (and/or nodule-like particles) equivalent diameter for any single unit, i.e. the diameter of a sphere that has the same volume as the single unit cell, has been calculated. The equivalent diameter distribution appears bimodal with two mean diameter values, respectively 110 μm and 475 μm. Majority of voids (and/or nodule-like particles) of sample 1 shows high sphericity (φ = 0.80-0.92) and the largest voids show the lowest sphericity.

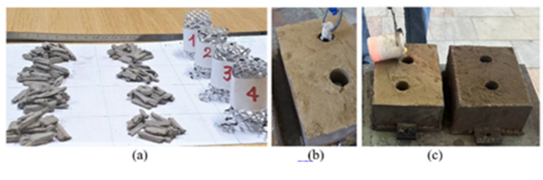

Figure 5: Sample 1 after casting: CT-scan images (a); pore and/or nodule-like particles size distribution (b).

4 CONCLUSIONS

In this initial research, the feasibility of casting aluminium-mineralized wood composites was evaluated. The wood chip can guarantee the formation of a light component core, thanks to the low reactivity of the wood, when pyrolyzed, with liquid aluminium. The casting process highlighted some critical issues that can be addressed by improving the pouring step and optimizing the architecture of the AMW-based components. Our future efforts will focus on overcoming these problems and, also, optimizing materials and components.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Laboratory of Foundry Technologies of Tashkent State Technical University for aluminum alloy casting, and Prof. Sara Ferraris of GLANGE Research Group of the Institute of Materials Physics and Engineering, Department DISAT of Politecnico di Torino, for SEM-EDS analysis.

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