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Technical Paper

Cost modeling and optimization of a manufacturing system for mycelium-based biocomposite parts

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ABSTRACT

A manufacturing cost model is created that includes all labor, material and overhead costs for novel mycelium-based biocomposite sandwich structures produced by a commercial firm. This model is implemented through a spreadsheet to calculate the equivalent uniform annual costs (UAC) of all manufacturing facilities. A simulation model of the manufacturing line is then implemented based on all these costs as well as system parameters experimentally measured from real manufacturing operations. The Tabu search method is utilized to search for the best manufacturing configuration including optimal number of machines and workers for each manufacturing step under both the current and projected production situations. The optimal solution can be used by the spreadsheet tool to calculate the net cost of each manufactured part and determine a proper retail price. The manufacturing system presented and associated models can be used by manufacturing personnel to assess the commercial viability of bicomposite parts.

1. Introduction

Advanced polymer matrix composites (PMCs) are comprised of strong, rigid reinforcements (e.g., glass and carbon fibers) bonded together by durable polymers (e.g., epoxy, polyester, nylon) to form laminate skins, which can then be made into sandwich structures using lightweight cores (e.g. honeycomb, balsa). These materials provide significant benefits over conventional engineering materials (e.g., steel and aluminum alloys), such as high stiffness-to-weight and stiffness-to-strength ratios and tailorable mechanical, thermal, and physical properties. While there is potential for significant growth of PMC use in a myriad of industrial markets [1], there are also significant issues that limit this growth as well. Because PMCs are either derived from non-renewable resources (e.g., reinforcements and resin made from petroleum and natural gas) or harvested from limited natural resources (e.g., most balsa wood used for cores is harvested in tropical regions of South America such as Ecuador), constituent materials of most conventional composite material systems are typically expensive and subject to price and supply fluctuations. Manufacturing costs for composites are also high because of industry's reliance on manual processing. Furthermore, synthetic composites have poor end-of-life options due to the difficulty of separating the mixed material back into its constituent parts. The only economical options currently are burning for fuel, landfilling, and in rare cases, regrinding to act as filler material.

An ideal situation for companies interested in designing and manufacturing sustainable products would be readily available composite materials consisting of all bio-derived constituents and manufactured using bio-inspired, low-energy processes. This idea has been suggested by many researchers (e.g., Ref. [2]) and serves as the inspiration behind the work described in this paper. Rensselaer Polytechnic Institute (Rensselaer) and an industrial collaborator have developed new and unique mycocomposite based sandwich structure biomaterials and associated manufacturing processes. Using mycelium to bond natural textiles as reinforcement skins and agricultural waste together as core, and then infusing the skins with commercially available bioresin to provide strength (if needed), viability of a 100% recyclable or biodegradable composite sandwich structure at the end of its service cycle has been demonstrated [3–5].

Mycelium, "the vegetative part of a fungus, consisting of a mass of branching, thread-like hyphae [6]," can act as a natural binder for biocomposite materials. It digests and bonds to the surface of damp agricultural byproducts in five to seven days at standard temperature and high humidity conditions without additional energy

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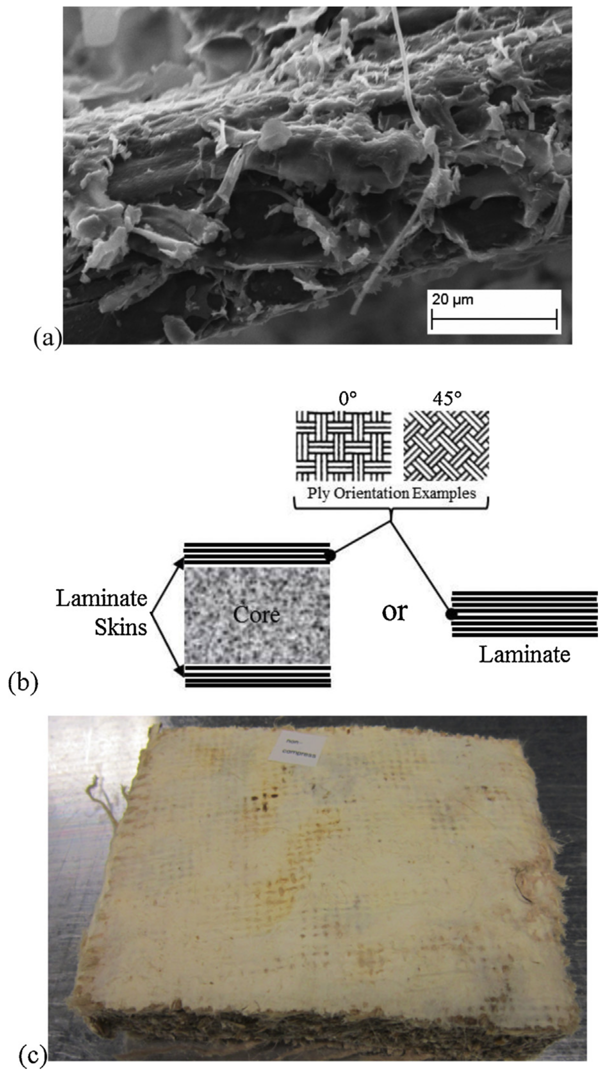

Fig. 1. (a) SEM image of mycelium hyphae growing on a natural fiber [6], (b) schematic of biocomposite sandwich and laminate structures, and (c) a mycocomposite sandwich structure.

input to adequately colonize reinforcement fibers and core material, thereby acting as a natural, self-assembling glue [7]. An SEM image of mycelium hyphae growing on a natural fiber is shown in Fig. 1(a). Following colonization, water is driven off and the mycelium is inactivated (killed) by drying the composite at high temperature (>80 °C) in a convection oven for a certain period of time. The resulting inactivated fungal network of threadlike cells bind together natural fiber reinforcement to form laminates (bound layers of reinforcement) and organic waste used as core material to form sandwich structures (attaching two thin but stiff skins to a thick, lightweight core), as shown in Fig. 1(b). These "mycocomposites," shown in Fig. 1(c), are reasonably rigid without infused resins: longer colonization leads to stiffer and stronger structures, and a smoother surface can also be achieved through full colonization [8]. To make truly structural sandwich parts, the myceliated core and dry reinforcements can be used as unitized preforms for resin infusion processes (e.g., resin transfer molding).

The main advantages of mycocomposite materials made using natural fibers (e.g., jute, flax, BioMid fiber, etc.) over traditional synthetic composites are: low cost; low density; competitive strength, tensile and impact mechanical properties, reduced energy consumption, the potential for CO_2 sequesterization if done at large scale, and perhaps most important of all, biodegradability [3–5,8]. The low-embodied-energy production process used for mycocomposites makes them cost competitive with synthetics, but the material is inherently sustainable since it comes from completely renewable sources and will biodegrade under the proper conditions or can be recycled into feedstock for packaging or composite core material (thus diverting waste from landfills). Mycocomposites are inherently safe–the material is stable when exposed to high temperatures (200–400 °C ignition point range) or ultraviolet radiation, and the use of vegetative tissue prevents the formation of spores (a potential allergen and friable particle) if it is made inactive (i.e., killed) before fruiting bodies form [7].

In this paper, qualitative and quantitative details of a seven-step manufacturing system, both processes and equipment, for producing biocomposite sandwich structures are presented and used in a manufacturing cost model for system optimization. Manufacturing trial runs are performed to measure all manufacturing parameters such as cycle time, numbers of workers required for each machine, and percentage of defective products for each step. A spreadsheet (Microsoft Excel) model populated with experimentally measured labor, material and overhead costs calculates the equivalent uniform annual costs (UAC) of all manufacturing facilities. Then, a manufacturing line cost model is created using discrete event simulation software (Arena® from Rockwell Automation) for optimization simulations to determine the optimal number of machines to buy and workers to hire for each manufacturing step. These optimized values are input back into the spreadsheet model to calculate the net cost of each manufactured part and required retail price. The general approach and example are intended to help inform researchers and practicing engineers on state-of-the-art in biocomposites manufacturing and guide them in optimizing production with the proposed manufacturing approach or something similar using a system model.

2. Manufacturing method for producing mycelium-based biocomposite products

2.1. Manufacturing product scenario

To fully demonstrate the manufacturing system by providing specifications for manufacturing tools and equipment, a commercially viable benchmark product, i.e. the sole of the beach sandal (Fig. 2), was chosen.

2.2. The seven-step manufacturing system

The aforementioned manufacturing systems consists of the following seven steps: (1) cutting natural fiber reinforcement in textile or mat form to the desired ply shape; (2) pre-impregnating each ply with a natural glue; (3) using heated match tools to form, sterilize, and solidify flat stacks of pre-impregnated plies into integral tooling; (4) filling integral tooling (thereby eliminating the need for dedicated molds) with agricultural waste pre-colonized with mycelium; (5) allowing the growing mycelium to bind together and grow into all constituent components under the right conditions to form a completely unitized sandwich preform or part; (6) drying and inactivating (killing) live mycelium in the mycelium-bound structure; and (7) infusing natural resin into the reinforcement skins followed by resin curing if higher part stiffness is required. For example, the manufacturer might want to infuse the sandal sole with a compliant resin to improve durability and wear characteristics. There is significantly less energy required with this approach compared to the manufacturing of synthetic composites. All seven steps are shown schematically in Fig. 3 and discussed in the next section.