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Investigation into the material properties of wooden composite structures with in-situ fibre reinforcement using additive manufacturing

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A B S T R A C T

In contrast to subtractive manufacturing techniques, additive manufacturing processes are known for their high efficiency in regards to utilisation of feedstock. However the various polymer, metallic and composite feedstocks used within additive manufacturing are mainly derived from energy consuming, inefficient methods, often originating from non-sustainable sources. This work explores the mechanical properties of additively manufactured composite structures fabricated from recycled sustainable wood waste with the aim of enhancing mechanical properties through glass fibre reinforcement.

In the first instance, samples were formed by pouring formulation of wood waste (wood flour) and thermosetting binder (urea formaldehyde), with and without glass fibres, into a mould. The same formulations were used to additively manufacture samples via a layered deposition technique. Samples manufactured using each technique were cured and subsequently tested for their mechanical properties. Additively manufactured samples had superior mechanical properties, with up to 73% increase in tensile strength compared to moulded composites due to a densification of feedstock/paste and fibre in-situ directional alignment.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, is a layer by layer fabrication of 3D objects from a digital model. During the process, material is laid down in individual layers; each layer is bonded/fused together through various techniques (sintering, melting, curing, chemical reactions etc.) [1]. This differs from subtractive manufacturing techniques such as machining that remove material which is considered to be an inefficient process in regards to material utilisation. AM technologies make it possible to build a large range of functional components with complex geometries which may be difficult, or even impossible, to achieve using conventional methods. Furthermore, manufacturing development cycles can be shortened when using AM, thereby reducing productions costs [2]. AM technologies have been involved in various applications in areas such as aerospace [3], automotive [4], artistic design [5] and biomedicine [6]. Materials commonly used in AM are often plastic [7] or metals based [8]. Although these additive processes are known for their low material waste during part manufacture, the creation of this feedstock is often through inefficient means. In contrast, there are currently only a few commercially available materials that are created from natural feedstock [9].

The AM of wood waste presents an opportunity to create 3D components from a cheap and sustainable source with limited material losses during processing. Wood flour is a typical wood waste and is processed commercially from post-industrial processes such as chips, sawdust and planar shavings. Unlike the larger sized chips, fibres and flakes, which are typically used in combination with thermosetting adhesive resins to produce wood panel products, wood flour is commonly used as a reinforcing filler in thermoplastic composite materials [10–12]. Wood-thermoplastic composites have become a widely recognised commercial product in construction, furniture and other consumer applications [13]. Wood-plastic composite components may be produced from a variety of different techniques such as injection-moulding [14], compression moulding [15], and extrusion [16]. The extrusion technique allows for net-shape components to be manufactured

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additively. There are several patents claiming to manufacture wood products via AM. Here, combinations of wood flour/fibres and variety of plastics such as acrylonitrile butadiene styrene [9,17], polylactic acid [9,17], and polypropylene [9,18] are used as the feedstock materials, together with a range of additives such as coupling agents, plastisizers, dispersants and lubricants. A further patent describes a method to produce wood products by which a binding agent is deposited via an ink jet printer head onto layers of wood powder [19]. However, the properties of the printed product are not reported.

In addition to thermoplastics, there are many other wood binders such as thermosetting resins and inorganic cements which are used in the production of wood composite materials [20,21]. Thermosetting adhesives have advantages over thermoplastic adhesives as they offer enhanced product qualities such as improved temperature resistance, resistance to deformation and superior mechanical properties [22–24]. Consequently, they are the preferred adhesives in the production of materials for structural applications such as wood panel products (e.g plywood, strandboard and fibreboard). AM of wood using adhesives other than thermoplastics has been reported [25]. However, there are limited studies which detail the methods used and which examine the mechanical properties of the printed product [26]. One such study describes how thin layers of wood chips/inorganic binder are bonded together to produce a solid of desired shape [21]. Bonding and hardening is brought about by the use of aerolised water as an activator on each layer. Binders investigated included gypsum, sodium silicate and a variety of cements. Investigators [27] have combined beech wood pulp with a starch binder (hyroxypropyl) to form a paste that was extruded/deposited with a syringe to form 3D wooden structures. However, due to the binder used, samples were very weak (maximum tensile stress of 3.5 MPa) and held similar properties to that of wood cements. Another work extruding wood pulp [28], used varying proportions of beech wood mixed with polyvinyl acetate and urea formaldehyde. It was found that the bending strength and stiffness of formed 3D parts improved when the urea formaldehyde binder was used, however properties were not affected by the amount of wood pulp used within the composition. This and other studies [29] conclude that material properties need to be improved in order for additively manufactured wooden structures to be suited for large structural applications.

Although the products are not, as yet, of sufficient mechanical strength suitable for many engineering applications, research has demonstrated that wood/adhesive composites can be produced by additive manufacturing. Furthermore, additive manufacturing technologies offer the possibility of inducing the alignment of fibrous materials within a product to enhance mechanical strength. Indeed, Compton and Lewis [30] reported the alignment of high aspect ratio fibres in epoxy resin using a 3D printing method, yielding improved mechanical properties along the printing direction. In this paper, we explore the applicability of an additive manufacturing technique to exploit potential fibre alignment within wood-thermosetting binder composites in order to improve mechanical properties.

2. Methodology

The creation of 3D printed components from wood flour and thermosetting binders was achieved through extruding these formulations, in a form of a paste, through a fine nozzle. Wood flour was selected as the wood component of the composites as it is considered a cheap and sustainable source of wood waste. Furthermore, the relatively small size of wood flour particles, compared to other wood wastes, make it suitable for 3D printing via extrusion through a nozzle. Urea formaldehyde was selected as the binder material. It is a traditional wood glue, commonly used as a thermosetting resin in the manufacture of panel products [20]. It was anticipated that the addition of strength enhancing fibres to the formulations would improve the mechanical properties of the composites [31] and, therefore, the effect of incorporating glass fibres into the composites was investigated. The mechanical properties of these 3D printed composites were subsequently examined and compared to non-printed, moulded composites prepared using the same formulations.

2.1. Materials

Wood flour waste feedstock was purchased from Eden Products Ltd, Middlewich, Cheshire, UK. This product (EPWF 110) is a waste wood from European white softwood (South Germany). The particle size distribution of the wood flour fibres was obtained using a sieving technique (Retsch AS200 sieve shaker), yielding a d_{50} (median) size value of 75 μm (it should be noted that this value obtained via sieving refers to the shortest physical dimension of the wood flour fibres). The wood flour samples were stored at a constant temperature of 21 °C and the moisture content was determined to be 14%. This value is within the accepted level for use with wood adhesives (<15%) and, therefore, adhesive performance would not be compromised. Urea formaldehyde (CASCORIT 1205) and hardener 2545 were both purchased form Glues Direct, UK. The pot life of the urea formaldehyde/hardener system is 8 h at room temperature and pressure, allowing sufficient time for formulation preparation and 3D printing of the pastes. Glass fibres (Vitrostrand), of approximately 100 μm in length, were purchased from East Coast Fibreglass, UK.

2.2. Composite manufacture

2.2.1. Additively manufactured composites

2.2.1.1. Preparation of formulations. A formulation of 13%wt/wt wood flour in urea formaldehyde was used. This had a viscosity that was low enough to be extruded/deposited through the nozzle easily, but also held a suitably high level of viscosity, enabling the dispensed product to maintain its shape prior to curing. The urea formaldehyde and hardener were mixed thoroughly at room temperature at a mixing ratio of 100 pbw urea formaldehyde: 20 pbw hardener. After degassing, the wood flour was added to the adhesive at room temperature and mixed thoroughly by hand using a wooden spatula.

Secondly, a formulation consisting of 8.8%wt/wt wood flour and 10%wt/wt glass fibres in urea formaldehyde was prepared. As with the non-glass fibre paste, this paste could be extruded/deposited easily through the nozzle whilst maintaining its shape before curing. Table 1 details the composite formulations in terms of weight fraction, volume fraction and density.

2.2.1.2. Additive manufacturing via extrusion/deposition. Printing via extrusion was carried out at room temperature (21 °C) using a Fisnar robot 7400; a 3-axis robot with a working area of 400 × 400 × 100 mm. A schematic of the process is shown in Fig. 1. The operating parameters (printing co-ordinates, printing line speed of 15 mm/s) were controlled using Smart Robot Edit software (Fisnar) running on a PC. The formulations were prepared and placed in a syringe barrel. The barrel was then attached to a pneumatic general purpose dispenser (Fisnar JB113N), connected to a compressed air supply (20psi). The dispenser was interfaced with the robot and controlled the dispensing pressure. The syringe barrel containing the paste was then placed in the barrel holder on the robot and a 1.6 mm diameter nozzle attached to the bottom of the barrel. Rectangular samples (80 mm × 10 mm x 2 mm) were