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Review

Fine grinding of wood – Overview from wood breakage to applications

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ABSTRACT

Due to its abundance, wood is the pre-eminent lignocellulosic raw material for a sustainable bioeconomy based society. Wood is widely used as fuel, construction material, and raw material in cellulose and lignocellulose based products. Besides the established uses of wood powder, like co-firing with coal and biofuel production, there are also novel uses and process applications, e.g., advanced wood-plastic composites and biochemical production are emerging for which the pulverization or fine grinding of wood is an essential pre-treatment step. Due to the tenacious nature of the wood matrix, size reduction is an energy intensive process and thermal or chemical pre-treatment may be needed to improve economy.

This paper provides a broad overview of the fine grinding of wood. First, wood breakage mechanisms and the mechanisms of size reduction are presented, followed by fine grinding techniques and wood pre-treatment methods. A comparison of the specific energy consumption of wood fine grinding in both a gaseous and liquid environment is illustrated. Additionally, examples are given of the role played by pre-treatment methods in decreasing energy consumption. The particle aspect ratio is discussed briefly. Finally, the use and requirements of wood powders in various applications are discussed.

1. Introduction

Social and political incentives for a carbon neutral and environmentally sound society lie behind the impetus to develop more sustainable products from renewable biomaterials. Because of its abundance, wood is the first choice as a renewable non-food source of lignocellulosic biomaterial. The FAO 2010 survey reports that 31% of the total land area of the Earth is covered by forests [1], accounting for about 50% of terrestrial gross primary production i.e. a carbon flux produced by terrestrial plants through photosynthesis [2] and 80% of total plant biomass [3].

Wood is widely used as fuel, construction material, and raw material in cellulose and lignocellulose based products such as paper and board. For many applications, wood has to be pre-treated by grinding it into a particulate form to produce 'wood powder' or 'wood flour'. Mechanical grinding of lignocellulosic substances such as wood leads typically to a fine particle size, various particle shapes, high specific surface area, and sometimes low cellulose crystallinity, depending on the energy and grinding mechanism applied as well as the grinding conditions and raw material properties. Grinding has a considerable effect on the storage and conveying properties of wood powder as well as its processability and suitability for use in a given application.

The definition of 'fine grinding' varies between different industrial areas [4–8]. For lignocellulosic biomasses, such as wood, the term 'fine grinding' has been proposed for product sizes less than 100 μm [9] but in other studies, the term has been used for product sizes up to 1 mm [10–12]. In this review, fine grinding is considered as the size reduction where the product mass median particle size is below 500 μm, which also means that virtually all particles are less than 1 mm. 500 μm is a practical limit in dry grinding that is difficult or even impossible to achieve with moist wood because size reduction will be limited by the agglomeration of particles, especially in mills where a particle bed is compressed, e.g., in ball mills and roller mills [13]. Additionally, 500 μm is the limit proposed for dividing biomass fuels into powders and granular materials [14].

In fine grinding, it is also common practice to classify processes as wet or dry. Wet grinding typically means the grinding of a material containing about 50% of uncombined water by volume [4], although other liquids apart from water can also be used. In practice, wet grinding involves the grinding of material that behaves like a liquid, i.e., a viscous fluid under compressive and shear stresses. In wet mills (e.g. ball mills, roller mills, disc mills) grinding is performed in a particle bed in which repeating squeezing and consolidation of the bed is responsible for particle breakages [15]. Dry grinding is related to grinding where material behave more like a solid, i.e., a rigid body under compressive and shear stresses, although the formation of particle bed is also possible.

Today, the main use of wood powder is in energy production by co-

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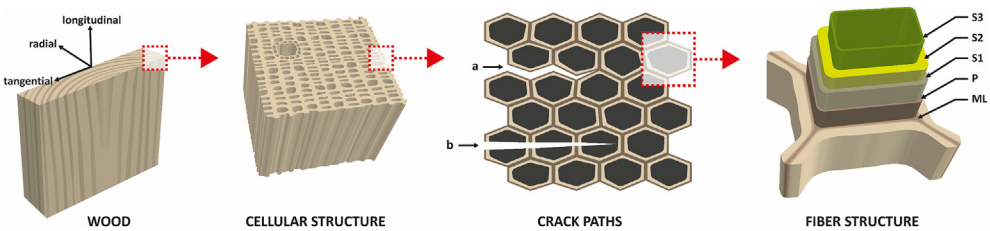

Fig. 1. Cellular structure of wood and an individual fiber. Crack paths are presented: (a) crack advance by cell separation (intercellular/interwall fracture), (b) crack advance by cell fracture (intracellular/transwall fracture).

firing with coal; however, there are an increasing number of applications where wood can be used in powdered form, such as thermoplastics [16] and paper products [17]. Research is ongoing to find novel ways to utilize wood powders, including the enzymatic, chemical, and thermochemical transformation of forest biomass for energy and chemicals.

As yet, there exists no comprehensive review of the fine grinding of wood. This paper aims to give a broad insight into the topic. First, wood breakage mechanisms and the mechanisms of size reduction are presented, followed by fine grinding techniques and wood pre-treatment methods. A comparison of the specific energy consumption (SEC) of wood fine grinding in both dry and wet is illustrated. Additionally, examples are given regarding the role of pre-treatment methods in decreasing energy consumption. A brief discussion is given of particle aspect ratio. Finally, the use and requirements of wood powders in various applications are discussed.

2. Mechanical properties and breakage behavior of wood

Wood is a composite material both on macroscopic and microscopic levels (Fig. 1). The fibers forms cellular structure glued together by lignin-rich middle lamella. Additionally, individual fibers are composites as such since cell wall is composed variously aligned layers of cellulose microfibrils - cross-linked together by hemicellulose - in a lignin matrix. Rheologically wood is a viscoelastic material. The viscous behavior causes internal friction, which converts most mechanical energy imposed on it into heat [18,19] that holds true also with brittle material [20].

2.1. Stress-strain behavior of wood

Due to the anisotropic structure of wood, the mechanical properties of wood vary depending on the loading direction (see Fig. 1, left) [21]. Fig. 2 illustrates typical stress-strain curves for spruce wood in radial,

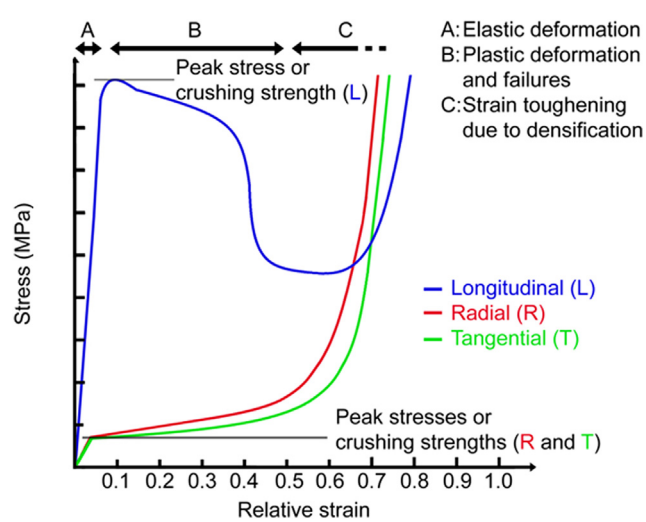

Fig. 2. Illustration of typical stress-strain curves for spruce wood under tangential, radial, and longitudinal compression [22].

tangential, and longitudinal compression [22]. The stress-strain curves shown have some general features that have been found for various other wood species under compression [23]. Linear-elastic behavior prevails at the beginning of deformation (A), but when the stress reaches the peak value, plastic deformation and failures take place (B). The plateau of the stress-strain curves relates to a progressive crushing of the wood, encompassing plastic deformation, during which a substantial growth in density is seen due to collapsing of the cells. This allows the denser wood to resist compression, as can be seen in the form of strain toughening (C) in the stress-strain curve.

2.2. Wood breakage

At the macroscopic scale, fracture mechanics of wood is typically divided into three modes of loading that lead to different forms of failure behavior [24] shown in Fig. 3. Pure tension failure is energetically more favored than pure shear failure in wood. A reason for this may be energy losses caused by friction between the fractured surfaces brought about by shear loads [25]. On the other hand, mixed mode loading (modes I and II) can lead to failure that is energetically more favorable than pure tension failure [26], since in this type the initial crack propagation always takes place along the longitudinal axis [27].

Fracture of wood studied at the macroscopic scale can be explained by phenomena at the cellular level. However, knots, growth rings and flaws may cause deviations and interpretation is not always straightforward.

The fracture force needed is dependent on the loading direction. When stress is perpendicular to the longitudinal axis, the wood breakage may occur as intercellular failure due to the separation of cells from each other by peeling. This means the crack propagating mainly via the compound middle lamella, (intercellular fracturing, see Fig. 1), [28,29]. When tension is perpendicular to the longitudinal axis, breakage of the wood requires stress more than 1 MPa, but much less than 10 MPa [30–33]. In the case of tension parallel to the longitudinal axis, for the breakage of the wood or of a single tracheid is required stress over 30 MPa [30,34]. Transwall (intracellular) failure takes place [35–38], i.e., the fracture path intersects the cell wall [39] (see Fig. 1).

Even though there are considerable differences in the breakage behavior of wood in different directions, in practical grinding it is difficult to utilize this material property of wood, since wood particles are typically more or less randomly oriented in the grinding zone. In particle beds, however, elongated particles have a tendency to be oriented perpendicular to the stressing element.

2.3. Effect of moisture, temperature and time under load

As a viscoelastic material, wood response to mechanical treatment is affected by temperature, moisture, time under load, and the number of stressing events. Internal friction causes energy loss, which is significantly higher for water-saturated than for air-dry wood, even at temperatures below 30 °C [18]. The glass transition point of such wood components as amorphous cellulose, hemicelluloses, and lignin has significant dependence on the moisture mass fraction of the wood [31] while crystalline cellulose has not [40].

Above the glass transition temperature, the physical state of the

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