Chapter 1. Project Description

1.1 Introduction

Synthetic composite panels, such as carbon or glass fiber reinforced laminates, perform well in adverse conditions where the durability and the exceptionally good directional properties of these materials give an advantage. One of the reasons for the widespread acceptance of these man-made materials is that the properties can be tailored to fulfill specified strength or deformation design requirements. Substantial research effort was spent to establish design standards and to optimize the performance of synthetic composite panels (Jones 1997, Hayer 1998). Although several high-value, engineered wood products evolved in recent years, these composites perform below their ultimate capabilities, due to the lack of optimized manufacturing and design procedures. One of the reasons is that wood-based composites add to the complexity of the production and design due to the variable nature and hygroscopic behavior of the raw material. Considerable improvements can be observed in the manufacturing and quality of these products as the process becomes more automated. However the design and production parameters are still mainly based on empirical "trial and error" experimentation with the manufacturing line. This empirical approach is expensive, time-consuming, and valid only for one set of manufacturing equipment and type of raw material. Recently, with the advent of powerful computers, more emphasis has been given to process modeling. The use of computer models has provided better understanding of several industrial processes, and the simulation of situations never considered before have resulted in innovative process improvements. The motivation of this study is to establish a process simulation tool based on fundamental engineering principles, which connect manufacturing variables with the properties of wood-based composite panels. The simulation model can assist to make decisions on production parameters on a more rational basis, and it can help to optimize the production process to improve the final properties of wood-based panels.The process modeling approach may improve the performance of existing products and lead to the development of new ones.

1.2 General Structure of the Hot-Compression Model

The overview of the main mechanisms present during the production of wood-based composites can identify the most influential stages of production. The mat formation involves the deposition of random size and shape wood elements (e.g. flakes) on a continuous conveyor belt. Final panel density and thickness determine the amount of flakes on a unit area. The deposition of the wood elements is not uniform, voids are present as the flakes are tilting and bridging, forming a loose mat structure. The horizontal density distribution of the panel is the most obvious evidence of the randomness of the mat formation process. During conventional hot compression the loosely formed mat is compressed to a target thickness between two metal platens under elevated temperature and pressure. The heat is conducted from the hot platens to the interior of the mat. High temperature and adequate time is necessary to cure the thermosetting adhesive at the core of the mat, which will in turn determine pressing time. The high temperature at the face of the panel evaporates the water present in the flakes. The vapor moves from the face towards the colder center of the mat, where it condenses, while releasing its latent heat, and further enhancing the temperature rise in the middle. Migrating heat and moisture also soften the polymers present in the cell wall. The plasticizing effect on the viscoelastic compression properties are different at different horizontal layers of the mat due to the uneven moisture and temperature distribution. The most notable result is that the softened flakes undergo varying degrees of consolidation forming a vertical density gradient through the thickness of the panel. Detailed understanding of these simultaneous mechanisms, and especially their interactions, is necessary to improve the properties of wood-based composite products, as well as reducing the pressing time. The most emphasis during the model development was given to the characterization of the mat formation and hot-compression stages of the production process.

The most widely used approach to model a complex phenomenon is to break it down into smaller, easier-to-manage parts. The hot-compression model was developed based on this modular concept. The hot-pressing operation was subdivided into modules, and the modules are connected to the general structure of the hot-compression model as depicted in Figure 1.1.

The following modules were identified in the model:

a.) mat formation,

b.) simultaneous heat and mass transfer of porous solids,

c.) viscoelasticity of polymers,

d.) transverse compression of cellular materials,

e.) adhesive cure.

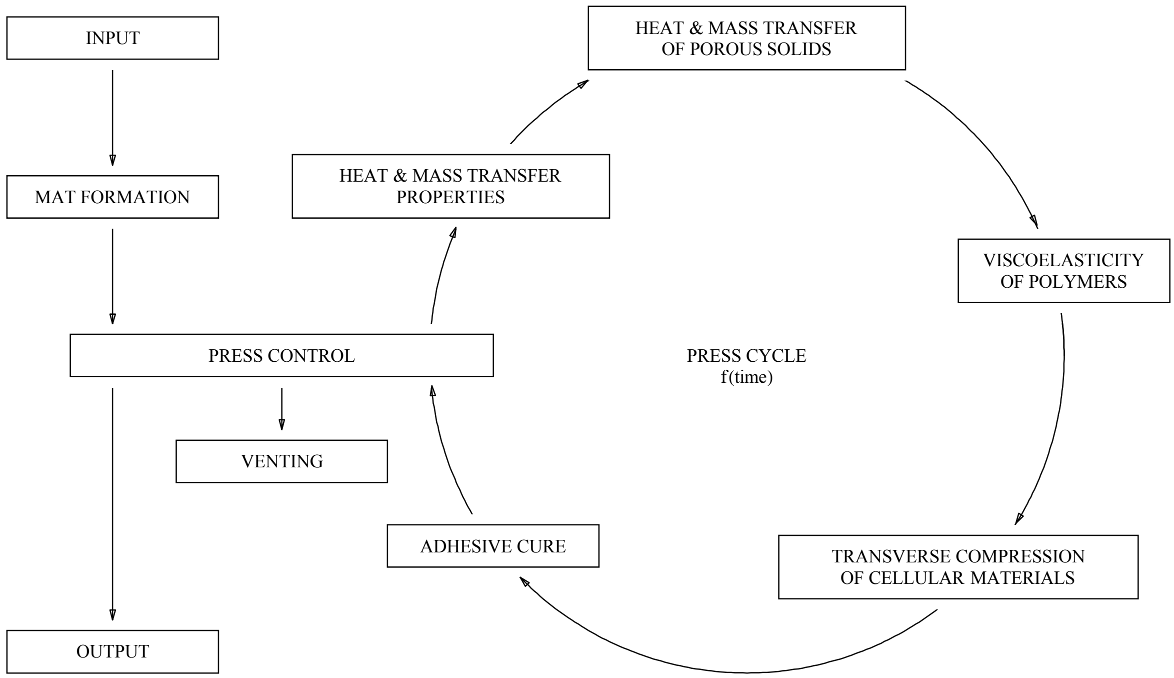

Figure 1.1. The general structure of the model.

The individual modules of the model have been researched intensively, and a considerable amount of information has been collected to better understand the different physical phenomena involved during the hot-compression. Based on this knowledge, several mat consolidation models were developed with varying complexities over the last three decades. These models focused on different aspects of the process and either the mat formation (Lang and Wolcott 1996a, Dai and Steiner 1993, 1994a, 1994b), the heat and moisture transfer (Humphrey and Bolton 1989), or the nonlinear consolidation (Lang and Wolcott 1996b, Lenth 1996a, 1996b) of the mat was addressed. However, a comprehensive model describing the manufacturing process of wood-based composites is still missing. Therefore, the aim of the research was to present a working model for the hot-compression of wood-based composites and to validate the model to a wide variety of pressing conditions.

1.3 Technical Objectives of the Research

The general objective of the research was to develop a comprehensive model based on engineering principles to describe the critical stages of the wood-based composite manufacturing process. The overall model was designed to describe the mat formation and the consolidation processes, involving probabilistic and deterministic modeling techniques. In order to achieve the general objective of this research, the following specific objectives were pursued:

1. Develop and experimentally validate a stochastic simulation model which describes the random nature of mat formation, using the Monte Carlo simulation technique.

2. Establish the mathematical relationship between the internal conditions of the mat (temperature, moisture content, pressure) and processing parameters, based on heat and mass transfer theories modified for hygroscopic porous solids.

3. Assess the degree of cure of the adhesive system during hot pressing, and include the effect of the exothermic reaction on the above mentioned internal conditions of the mat.

4. Predict the viscoelastic behavior of the mat during the consolidation process by modeling the flakes as polymers exposed to transient temperature and moisture conditions.

5. Apply the theories of transverse compression of cellular materials to address the nonlinear behavior of the mat during consolidation.

6. Using the results of objectives 4 and 5 to develop a combined model for monitoring and predicting the vertical density profile formation during the hot-compression process.

1.4 Rationale and Significance

The decreasing availability of old-growth forest resources has contributed to the substantial growth of the wood-based composite industry. Between 1996 and 1997 over 20 new structural wood-based composite mills were established in North America alone, an investment of $ 2 billion. The newest technologies were implemented in these mills, therefore they can utilize very broad timber species and also recycle wood, with a material use efficiency close to 100 %. The raw material requirement of these mills is renewable and can be cultivated in plantations as any other agricultural crop. Initially the primary objective of the composite industry was to utilize low quality logs and mill residues of other wood processing operations. Recently high-value engineered composites were developed that can compete successfully in the marketplace with other construction materials. The high quality products require tighter control of the production process, therefore it has to be better understood.

Wood and wood-based composites are complex systems. Solid wood has an intrinsic variability and it is anisotropic by nature. Additionally, wood interacts with the relative humidity and temperature of the ambient air. During the production of wood-based composites, several other processing parameters can affect the quality of the finished product. The most critical processes, where the final character of the wood composite material is attained during the production, are the formation and the hot-pressing of the flake mat. The interaction of the variables make the modeling of the production process a complex problem. These interactions are not well understood and this lack of understanding prevents optimal production of wood-based composites. The pressing schedules used by the industry are based on “trial and error” experimentation with the production process. These empirical results are valid only for one particular system of pressing equipment and raw materials. A more fundamental approach, which is based on basic engineering principles, can address the problem more rationally. A systematic analysis and optimization of the production parameters can result in improved material properties and increased production efficiency. Furthermore, the design information provided by the analysis can be used to manufacture new combinations of raw materials and implement new technologies, such as steam-injection pressing and radio-frequency adhesive curing.

1.5 Structure of the Dissertation

This dissertation is divided into seven chapters. Each chapter discusses the development or validation of an individual module of the overall model shown in Figure 1.1.

The development of the simulation model that describes the mat formation process is discussed in Chapter 2. The experimental validation of the Monte Carlo simulation process is also included.

Chapter 3 is devoted to discuss the development of the heat and mass transfer model. A two-dimensional mathematical model was developed that is capable of describing the changes of the internal environmental conditions within the mat. The validation and sensitivity study of this model are discussed in Chapter 4, including the critical physical and transport phenomena. A detailed description of the experimental work is also provided.

The vertical density profile formation during the pressing process is addressed in Chapter 5. The developed compression model involves several physical aspects of the consolidation process. The chapter provides a detailed description of the interacting parameters and the theoretical approach of the model development. Chapter 6 is dedicated to describe the experimental work for validation of the vertical density profile formation. It provides information about the experimental techniques, including γ-ray and x-ray densitometry used to validate the model. Comparison of the predicted and experimental data is provided.

Finally, Chapter 7 summarizes the entire research, discusses the corollary conclusions inferred from the analytical and experimental work, and considers future research needs.

In general, these chapters can be considered as stand alone documents. Consequently, each chapter contains an introduction, background, model development, material and methods, results, and conclusions sections. The relevant references and explanation of symbols used are listed at the end of each chapter. This research used SI units, in certain cases quantities are given in English units as well. The tables and figures follow the reference in the text. For quick identification an overall list of figures, tables, and symbols are provided at the beginning of this dissertation.

References

Dai, C., P. R. Steiner. 1993. Compression behavior of randomly formed wood flake mats. Wood and Fiber Sci. 25(4):349-358.

Dai, C., P. R. Steiner. 1994a. Spatial structure of wood composites in relation to processing and performance characteristics. Part II. Modeling and simulation of a randomly-formed flake layer network. Wood Sci. and Technol. 28:135-146.

Dai, C., P. R. Steiner. 1994b. Spatial structure of wood composites in relation to processing and performance characteristics. Part III. Modeling the formation of multi-layered random flake mats. Wood Sci. and Technol. 28:229-239.

Humphrey, P. E., A. J. Bolton. 1989. The hot-pressing of dry-formed wood-based composites. Part II. A simulation model for heat and moisture transfer, and typical results. Holzforshung 43(3):199-206.

Hyer, M. W. 1998. Stress Analysis of Fiber-Reinforced Composite Materials. McGraw-Hill, New York, N.Y.

Jones, R. M. 1975. Mechanics of Composite Materials. Hemisphere Publishing Corp., New York, N.Y.

Lang, M. E., M. P. Wolcott. 1996a. A model for viscoelastic consolidation of wood-strand mats. Part I. Structural characterization of the mat via Monte Carlo simulation. Wood and Fiber Sci. 28(1):100-109.

Lang, M. E., M. P. Wolcott. 1996b. A model for viscoelastic consolidation of wood-strand mats. Part II. Static stress-strain behavior of the mat. Wood and Fiber Sci. 28(3):369-379.

Lenth, C. A., F. A. Kamke. 1996a. Investigations of flakeboard mat consolidation. Part I. Characterizing the cellular structure. Wood and Fiber Sci. 28(2):153-167.

Lenth, C. A., F. A. Kamke. 1996b. Investigations of flakeboard mat consolidation. Part II. Modeling mat consolidation using theories of cellular materials. Wood and Fiber Sci. 28(3):309-319.