CHAPTER I

LITERATURE REVIEW AND SCOPE OF THESIS

1.1. Introduction

The engineering of modern composite materials has had a significant impact on their technology of design and construction. By combining two or more materials together, it is possible to make advanced materials which may be lighter, stiffer and stronger, and better materials to fulfill end-use requirements than any single material ever used before.

The structure of a wood flake composite mat may be defined as the geometric arrangement of the constituent flakes or strands in the mat. If only the mat structure is concerned, the mechanical properties of flakeboards depend primarily on the number of flake-to-flake contacts or flake-crossings and the physical properties depend primarily on the compression behavior of the mat. A better understanding of the internal mat structure will help us to characterize properties of such wood composites and to utilize them more efficiently.

Wood composites require consolidation during the manufacturing process in order to reach a certain strength. This process often leads to dimensional stability problems and higher than desirable panel densities which have a negative effect on production cost and weight. A critical, but not yet well understood factor in performance is the packing arrangement (i.e., orientation and position) of the wood elements in a mat. This factor is believed to affect the horizontal density variation (Suchsland and Xu 1989). More attention has been paid to this research area recently and a two-dimensional multi-layer flake mat model has been developed (Dai 1993, Dai and Steiner 1994a, b and c). Within this model, the formation of a short fiber composite mat was thought of as a random process due to the random nature of the constituent deposition. The structural properties of the flake network were random variables which could be characterized by Poisson and exponential distributions (Dai 1993).

However, most of the earlier studies in this area assumed uniform flake geometry and completely randomized orientation of flakes in the mat, which is not realistic. These results cannot be directly applied to commercial products, such as a three-layer oriented strand board (OSB) where the flakes are partially oriented.

In this thesis, emphasis was placed on improving the understanding of the relationship between horizontal density variation and properties of wood composite mats. To achieve this aim, mathematical models along with the computer simulation, robot mat formation and X-ray scanning techniques were used. Knowledge gained from the combination of the mathematical models, simulation and predefined mat structures made by a robot, and quantitative data on density distribution scanned by an X-ray system, will help to guide improvements in present mat forming technology and also provide some guidance of future wood composites development.

1.2. Literature Review

Wood products can be broadly classified into two categories: solid sawn products and reconstituted wood products such as flakeboards and fiberboards. The second category is the topic of the current study. The properties of different wood composites vary greatly depending on different raw materials, geometry and arrangement of their constituents and manufacturing parameters.

1.2.1. Density variation

Short element wood composites consist of wood elements inter-dispersed with voids in a manner that results in a distribution of density along the horizontal plane. In a mat, the density distribution can be further subdivided into a vertical component and a horizontal component. The vertical density distribution, which is the combined results of temperature, moisture, and compressive stress of wood perpendicular to the panel during hot pressing, has been extensively studied (Heebink 1972, Plath and Schnitzler 1974, Suchsland 1962, etc.) and well documented (Kelly 1977). The horizontal density distribution as well as physical and mechanical properties in the plane, such as thickness swelling, bonding strength, modulus of rupture and modulus of elasticity are determined by the geometry and arrangement of constituent elements (Dai and Steiner 1994a, 1994b and 1994c, Suchsland 1959, Xu 1994).

The two most important factors controlling the mean final density of a mat are the density of raw materials and the compaction of the mat in a hot press. The density of raw material can be assumed to be constant for a given wood species. However, the pressing operation eliminates many void volumes in a mat and consolidates the mat to a desired thickness. The compaction of the mat to an average density higher than the density of the raw material will allow better surface contacts among individual flakes in the mat (Kelly 1977). Suchsland (1959 and 1962) developed a statistical model for a flakeboard mat relating the degree of densification to flake geometry, relative void volume and the density of wood components. He concluded that a higher pressure is required to reach a desired density for narrower and thicker flakes as opposed to wider and thinner flakes and that the relative compression area, which is a portion of total mat area under compression, is a significant factor in developing bending strength in a flakeboard.

The distribution of total flake coverage varies randomly in a mat so that the regions of higher flake coverage are obviously compressed to a greater extent in comparison with corresponding regions of lower flake coverage when the entire mat is compressed to a given uniform thickness (Suchsland 1959). In randomly formed mats, the larger relative void volume corresponds to a larger flake length to width ratio (aspect ratio) and the smaller relative void volume corresponds to a smaller aspect ratio (Suchsland 1959).

1.2.2. Veneer strip model in a flakeboard mat

Suchsland and Xu (1989) demonstrated a model using parallel veneer strips to study the horizontal density variation in a flakeboard. This model is a layered mat with each layer consisting of a number of uniform size veneer strips organized in parallel with air space interspersed. The structure of a multiple-layer mat is the same as that of plywood, i.e. 90^o in any two adjacent layers. An increase in the interspersed air gap in the mat layers results in more severe variation of the horizontal density in the densified panel.

If we build a veneer strip mat in such a way that there is no air gap involved, the number of layers, *N*, will be achieved by the following equation

$$N = \frac{T}{M} = O(av) \qquad (1.1)$$

where

T = total number of veneer strips,

M = number of flakes in one layer, and

O(av) = average number of overlaps.

In order to characterize the variation of the number of veneer overlaps in a mat, some air spaces will be allowed in each layer. Therefore the total number of layers will be larger than that of the perfectly packed mat if the number of veneer strips remains the same, resulting in some points with more overlaps than others. The distribution of the number of veneer strips over any small area follows a binomial distribution (Suchsland 1959):

$$P(i) = \binom{n}{i} \cdot p^i q^{n-i} \tag{1.2}$$

where

$P(i)$ = fraction of total area over which the number of solid veneer elements equal i,

n = total number of flake layers,

p = relative wood volume of each veneer layer, and

$q = 1 - p$ = relative air volume of each veneer layer.

This model allows the systematic modification of the horizontal density variation and the evaluation of its effects on the quality of the densified and consolidated mat. Although this model has many limitations in the practical sense, such as flake position and orientation, it does reveal some important facts, such as overlaps and voids, in a randomly formed flakeboard mat and provides the basic concept for further model development.

1.2.3. Uniform flake randomly-formed mat

A mathematical model was developed to describe the structural characteristics of flakeboard, assuming a uniform flake size and a random formation process (Dai, 1993). Since wood flake mats or flakeboards can be considered as a number of vertically stacked layers in two dimensions, this model deals with the most basic structural units of an idealized wood composite - randomly formed flake layers. The random process here refers to a random flake deposition and a random flake orientation. In the spatial structure of the wood composite mat in relation to processing and performance characteristics, flake geometry will affect relative void volume in a mat. Orientation of elements plays an important role in optimizing directional strength properties and improving packing behavior. By developing a model which incorporates flake overlap probability together with linear and non-linear compression stress perpendicular to the grain for a column of randomly packed flakes, predictions can be made of the stress-strain behavior in a mat (Steiner and Dai, 1993).

In the two-dimensional mathematical model, the structure related concepts in each layer are described as: distribution of free flake length and distribution of void size (Dai and Steiner 1994a). The multi-layered spatial model allows calculation of the distribution of flake centers, distribution of flake area coverage, the distribution of local density averages, relative flake to flake contact area, internal stress and relative void volume (Steiner and Dai 1993). Most of these concepts are common to the structure of paper because of the similar structures in both flakeboard and paper (Kallmes and Corte 1960, 1961, 1963).

Distribution of flake centroids:

A randomly formed flake layer is defined as a horizontal plane with an area A where a limited number of flakes, N_f, with length l, width w and thickness t are independently deposited by a random process (Dai and Steiner 1994a). It is assumed that all the flakes are horizontally positioned and the total flake coverage area $A = N_f\, lw$. The flake centers in N_L multi-layers can be described by a Poisson process when the number of flakes ($N_L \times N_f$) is very large (Dai 1993). If a large network is divided into a number of small squares with area *S*, the probability of finding *i* centers in a square, *P(i)*, is defined by (Hall 1988):

$$P(i) = \frac{\bar{n}^{i}.e^{-\bar{n}}}{i!} \quad (1.3)$$

where

$\bar{n} = (N_L N_f)S / A$, the average value of flake centers in a square *S*.

Distribution of flake area coverage:

Since the mat formation follows a random process, some areas will inevitably have more than one flake, resulting in overlaps (Dai and Steiner 1994a). The distribution of these overlaps in any arbitrarily chosen point is also given by the Poisson distribution (Hall 1988), which is an approximation of the binomial distribution of **Equation** 1.2:

$$P_I(i) = \frac{\bar{n}_f^{i}.e^{-\bar{n}_f}}{i!} \quad (1.4)$$

where the mean number of flakes covering any point equals to $\bar{n}_f = \frac{lwN_f}{A}$ regardless of how the flakes are distributed over the area.

Distribution of free flake length:

The free flake length is defined here as the distance between any two adjacent flake crossings over one flake, which is analogous to free fiber length in paper structure. The distribution of free fiber length is considered to be related to the deformation behavior of paper and the void distribution (Kallmes and Bernier 1963). The number of crossings per fiber can be considered as the number of "anchors" which can influence the mechanical strength of paper (Corte 1982). The probability of free flake length (the distance between two adjacent intersects between m and $m + dm$) , $P_M(m)$, follows an exponential distribution (Dai and Steiner, 1994a, Hall 1988, Kallmes *et al*, 1960, 1963),

$$P_M(m) = \frac{e^{-\frac{m}{\overline{m}}}}{\overline{m}} \tag{1.5}$$

where

$\overline{m}$ = the mean distance.

Distribution of void size:

The basis for the void size distribution is the distribution of polygon areas generated by random lines (Miles 1964). The number of crossings is a statistical parameter, which provides the link to the mechanical properties of the network. For random points on a line, the distribution of gaps is of a negative exponential type (Miles 1964). For random lines in a plane, the distribution of inter-crossing distances is therefore also negative exponential (Deng and Dodson 1994). These crossing distances (free flake length) form the sides of polygons and the distribution of the polygon areas for random lines in a plane is given by (Kallmes 1960, Dai and Steiner 1994a)

$$P_v(a_v) = \frac{e^{-\frac{1}{\overline{m}}\sqrt{\frac{a_v}{a}}}}{2\overline{m}\sqrt{aa_v}} \tag{1.6}$$

where

a_v = the area of individual polygon (void) which is assumed to be proportional to the square of the free flake length m, i.e.

$$a_v = \alpha m^2$$

where

α = constant coefficient, obtained through mathematical derivation (Dai and Steiner 1994a)

$$\alpha = \frac{Ae^{(b-1)\bar{n}_f}}{2(N_c - N_f)\bar{m}^2}$$

where

A = the area of plane

N_f = number of flakes

N_c = total number of crossings

$b = \dfrac{1}{1+\bar{w}/\bar{l}}$ is the function of average length, $\bar{l}$, and width, $\bar{w}$.

The polygons, into which the area of the network is divided, provide the link to its porous structure and porosity properties. If in a large network each line is changed into a constant width of plane, some small polygons will disappear and larger ones will be reduced in size (Corte 1982).

Variation of local mass density averages:

A flake mat can be considered as a two-dimensional fibrous network with a structure exhibiting local variations of the area mass density (*MD*) in the horizontal plane. The mean mass density, *E(MD)*, over a mat area was obtained by Dai and Steiner (1994b):

$$E(MD) = \frac{N_f \, lwtD_f}{A} \tag{1.7}$$

The variance of regional mass density average, $Var(MD_a)$, is expressed as (Vanmarcke, 1983):

$$Var(MD_a) = g(s_x, s_y)Var(MD) \tag{1.8}$$

where

$g(s_x, s_y)$ is defined as the variance function of local density averages, which measures the reduction of the point variance *Var(MD)* under regional averaging,

$Var(MD) = t r_f E(MD)$, the variance of local mass density (Dai and Steiner, 1994b),

r_f is the flake density, and

t is the flake thickness.

Relative bonded area:

Since flake overlaps have a distribution of the form of **Equation** 1.4, areas with more flakes will be compressed during hot pressing more than the others. The relative bonded area, which depends mainly on the compaction ratio (the board density to flake density ratio) and flake thickness, is defined by Dai and Steiner (1993) as:

$$RBA = \frac{e^{-n_f}}{n_f - 1} \sum_{i=T/t}^{\infty} (i-1) \frac{n_f^i}{i!} \tag{1.9}$$

where

T = board thickness,

t = average flake thickness.

Relative void volume:

The void volume in a mat consists of two parts: voids between flakes and pores inside flakes. The total relative void volume, RV_t, in a board can be obtained by:

$$RV_t = \frac{V_v}{V_t} = 1 - \frac{r}{r_0} \tag{1.10}$$

where

V_v = void volume

V_t = overall board volume

r_0 = wood cell-wall density (relatively constant at 1.5-1.55 g/cm^3)

r = overall board density

The relative void volume between flakes, RV_{bf}, is determined as (Dai and Steiner 1993):

$$RV_{bf} = e^{-n} \sum_{i=0}^{T/t} (1 - \frac{i\,t}{T}) \frac{n^i}{i!} \tag{1.11}$$

therefore the relative void volume inside flakes, Rv_{if}, is calculated by subtracting the relative void volume between flakes from the total relative void volume, i.e.,

$$RV_{if} = RV_t - RV_{bf} \tag{1.12}$$

The total relative void volume decreases linearly with the increasing compaction ratio while the voids between flakes decrease dramatically with increasing compaction ratio.

1.3. Scope of Thesis

The scope of this research thesis consists of the computer simulation of wood flake composite mats, development of mathematical models for partially oriented mat structures and thickness swelling prediction, use of a robot mat forming system to make experimental mats, and application of X-ray scanning and gravimetric techniques to measure horizontal density distribution of the composite mats (**Figure** 1.1).

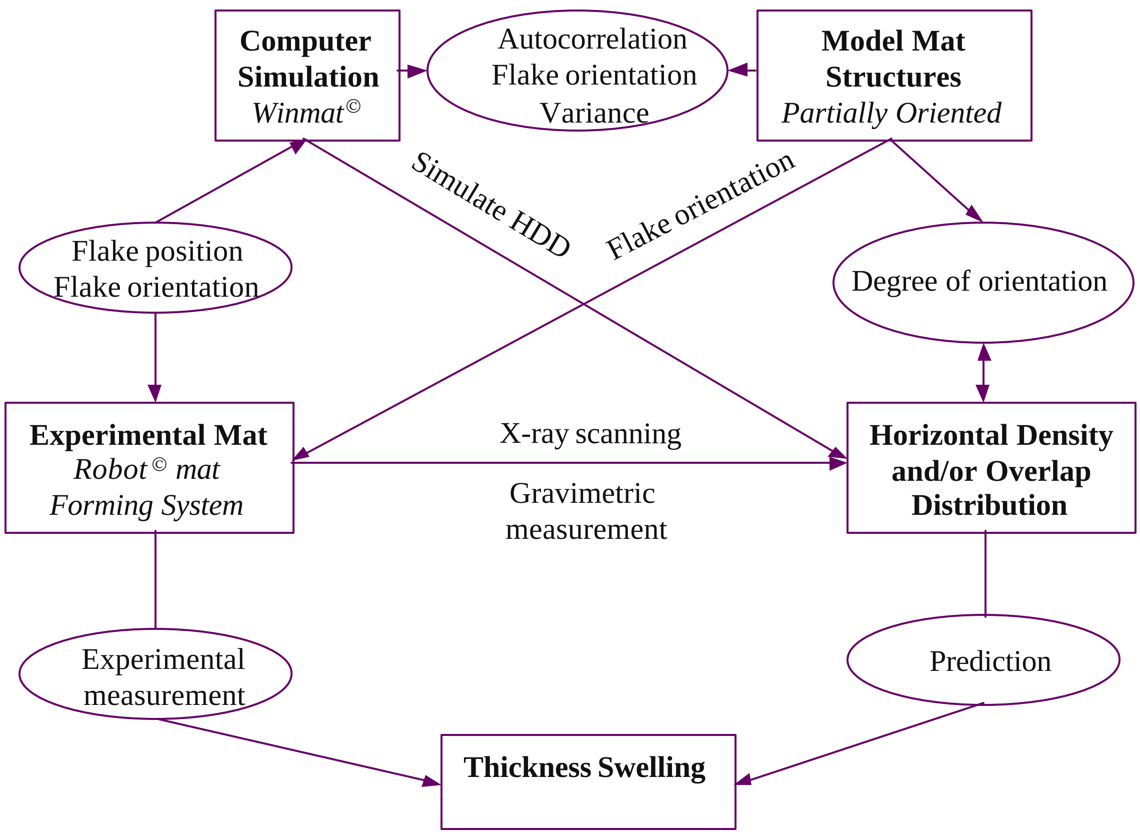

Figure 1.1 Scope of the thesis research

1.3.1. Definition of flake in mat network and computer simulation

Consider a thin flake with length l and width w arbitrarily located and oriented in space. The position and orientation of the flake can be defined by 1) the centroid coordinate of the flake, P (x, y, z), and 2) the orientation of the flake plane with respect to the XYZ Cartesian coordinate system. Further consider the flake plane on which the flake is resided, one can project a vector from the origin to the flake plane such that is normal to the plane. The vector will make an angle q ($0 \le q \le 90^o$) with respect to the z-axis. The projection of this vector onto the X-Y plane will make another angle j ($-90^o \le j \le 90^o$) with respect to the x-axis (**Figure** 1.2). Therefore the flake is well defined in the mat network by the five parameters (x, y, z, q, j).

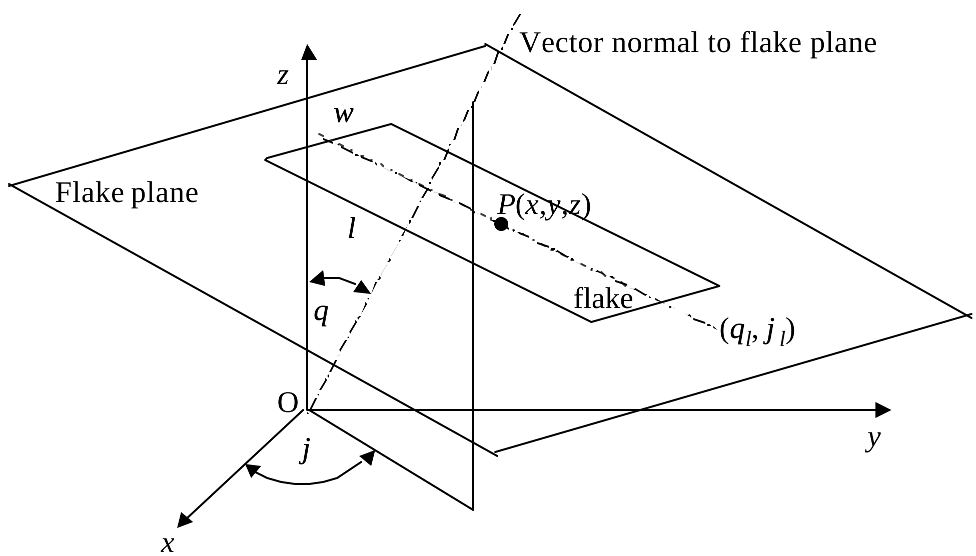

Figure 1.2 Flake position and orientation defined in three-dimensional space.

However, a flake can be oriented at any angle on this plane if no further restrictions are specified. Therefore, the direction of flake length is selected as a reference to the flake orientation. The center line in flake length direction can be expressed by q_l ($0 \le q_l \le 90^o$), the angle between the z axis and the line itself, and φ_l ($-90^{o} \leq \varphi_l \leq 90^{o}$), the angle between the x axis and the normal projection of the center line onto the X-Y plane (**Figure** 1.2). The position and orientation of a flake can therefore be explicitly described by seven parameters ($x, y, z, \theta, \varphi, \theta_l, \varphi_l$). However, there are only six independent variables because the normal axis of a flake is perpendicular to any lines on the flake plane. Their product of direction cosines equals to zero. It can be shown that the following relationship (**Equation** 1.13) holds for four orientation angles ($\theta, \varphi, \theta_l, \varphi_l$).

$$\sin\theta \cdot \sin\theta_l \cdot \cos(\varphi - \varphi_l) + \cos\theta \cdot \cos\theta_l = 0 \qquad (1.13)$$

From the formation point of view, the evolution of a mat is really a random array of flakes in three dimensions since the flakes are not always deposited in a plane normal to the direction of the applied pressure and some of them might stand on the edge or on the end (Suchsland 1959). However, once it is formed by a forming belt, the mat is essentially a layered structure (Suchsland 1967, Dai and Steiner 1994b). This can be seen crudely by delaminating a mat and the observation that almost all the flakes lie parallel to the horizontal plane of the mat. Here a "layer" is defined as the average coverage over an area A with the thickness of one flake, and a mat could be considered as a multi-layered random flake mat as a summation of a series of two-dimensional randomly formed flake layers.

Therefore, assuming all the flakes are deposited parallel to the horizontal plane (θ = 0) in a predefined area, $L \times W$ mm^2 plane, each flake has a definite position in the mat. The parameters needed to define the position and orientation of a flake in space are reduced to three variables, which can be described by x and y coordinates ($0<x\leq L$, $0<y\leq W$) for flake centroids and orientation angles φ ($-90^{o} \leq \varphi < 90^{o}$). The data (x, y, φ) can be numerically simulated by computer or the results from experimental measurements.

Based on this definition, a simulation program for mat formation process (***Winmat***©) and a program for controlling a robot mat former (***Robot***©) have been developed. This simulation work was carried out to study the nature of a random or partially random formation process of a mat. The variation of horizontal density depends mainly on the flake position and orientation in a mat, while the standard deviation of the horizontal density variation depends on the sampling zone sizes, that is, the smaller the sampling zone size, the higher the horizontal density variation. This part of the thesis work will be presented in **Chapter** II.

1.3.2. Partially oriented flakeboard mat network

The nature of the flake mat formation is a random process unless the flake orientations or locations are controlled or predefined. The concept of flake distribution is designed to facilitate description of the arrangement of flakes in a mat and such an arrangement is based on two dimensional or multi-layered models. A common feature of these models is the more or less implicit assumption that three-dimensional assemblies of flakes can be represented by superimposing two dimensional flake structures. The mechanical properties of the network are essentially dependent on the properties, geometry and compaction behaviors of the constituent flakes in a complex manner.

Two distribution functions are used for describing the flake orientations. One is the uniform distribution, which has an equal probability of choosing any angle within the range of $-q_1$ to $+q_1$, and the other is the Von Mises distribution characterized by a shape factor, called the concentration parameter k. Both distributions have extreme conditions, *i.e.*, completely randomized orientation when q is between -90^o and $+90^o$ or the concentration parameter $k \rightarrow 0$, and the perfectly aligned orientation when q is 0 or $k \rightarrow \infty$. However, the partially oriented flake mat network is used to refer to the conditions with $0 \leq q_1 \leq 90^o$ in the uniform distribution and with $k > 0$ but finite in the Von Mises distribution. Details will be presented in **Chapter** III.

1.3.3. X-ray scanning technique

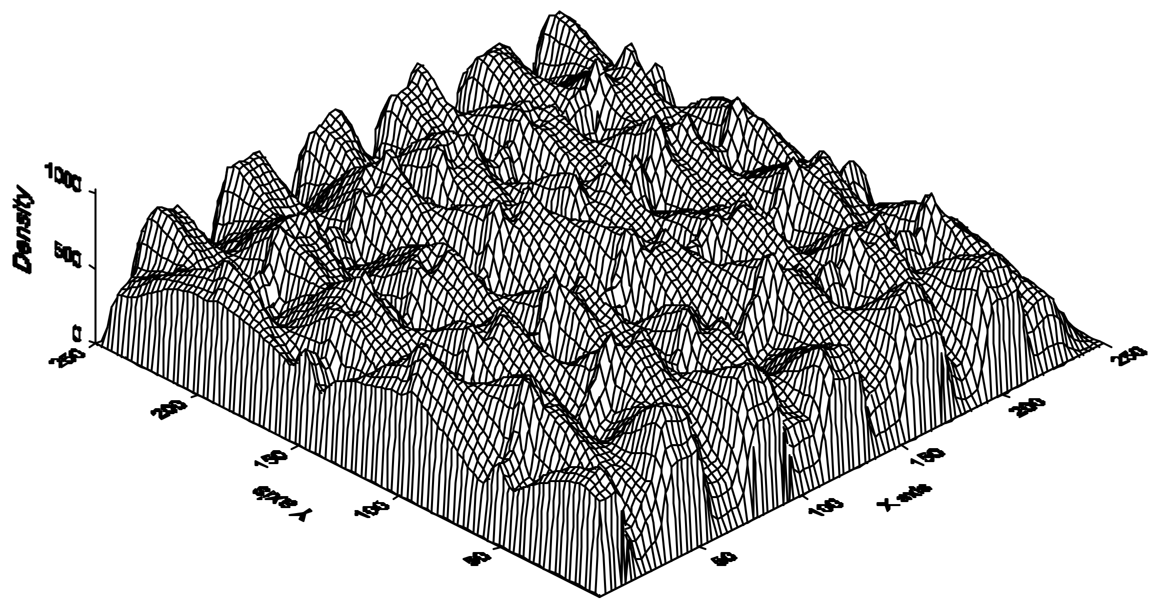

Figure 1.3 Horizontal density variation in a flake mat.

The horizontal density variation of experimental mats (**Figure** 1.3) was determined by the X-ray scanning technique. With the X-ray device used, a single line of data with 128 pixels (1 pixel = 1 byte) in 150 mm wide strip of material can be measured at a time. One measurement takes 1725 lines of data in a few seconds and stores it in one file. The noise can be reduced by averaging 1725 data at the same point. However, what we get from the scanned data is the voltage level representing the attenuated X-ray radiation. The voltage data is then calibrated and converted to X-ray intensity, which is used to evaluate the horizontal density distribution or overlap distribution. **Chapter** IV presents the detailed procedures and results from this study.

1.3.4. Thickness swelling

Thickness swelling is a physical property of a material subject to the absorption of moisture. It is a measure of the relative thickness change based on the original thickness. The thickness swelling model is derived from the strain and stress rate model proposed by Martenson (1994). Use is made of the fact that the definition of strain is the same as the definition of thickness swelling. The thickness swelling is then related to both relative moisture content and the density (or flake overlap) of flakeboard. More details will be presented in **Chapter** V.

1.3.5. Application of the model

Chapter VI presents a case study on how the models developed in the thesis can be used to analyze the characteristics of the simulated partially oriented flakeboard mats, simulated OSB mats and a commercial OSB panel. The specifications of these mats are given first. The partially oriented flakeboard model developed in **Chapter** III is then applied to predict the horizontal density distribution, void size distribution, autocorrelation function, variance function, degree of orientation and thickness swelling. Finally some future research work on the current model is discussed.

In the last chapter, **Chapter** VII, a brief summary on the general approach and the nature of the proposed model is given and some major conclusions are drawn based on the analysis presented.

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