Compression Molding of Short Fiber Composites

By

Suresh G. Advani

INTRODUCTION

FLOW MODELING

HEAT TRANSFER AND CURING

RHEOLOGICAL EFFECTS

FIBER ORIENTATION

INTRODUCTION

Technological Significance

Advantages:

no regions of high stress
longer fibers can be processed
wastes very little material
can produce large parts

Drawbacks

difficult to mold large intricate parts with deep undercuts
cannot produce very close tolerances
material handling
ease of automation.

Compression Molded Composite Materials

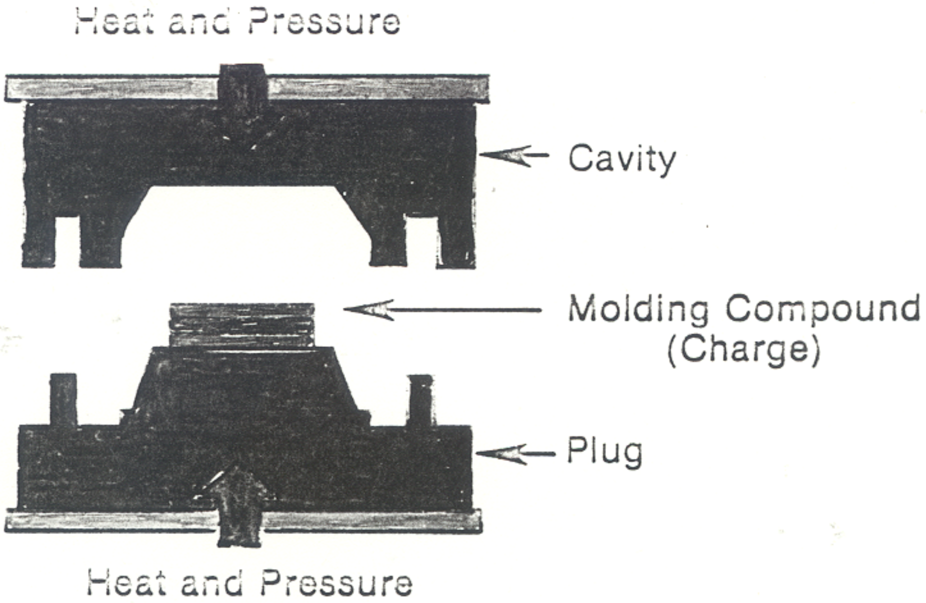
Thermoplastic forming

Thermoset matrices with short reinforcing fibers (SMC,BMC,DMC)

Thermoset matrices with continuous aligned reinforcing fibers

Stamping materials (thermoplastics with random fibers)

Traditional laminates usually with woven cloth



COMPRESSION MOLDING SET-UP

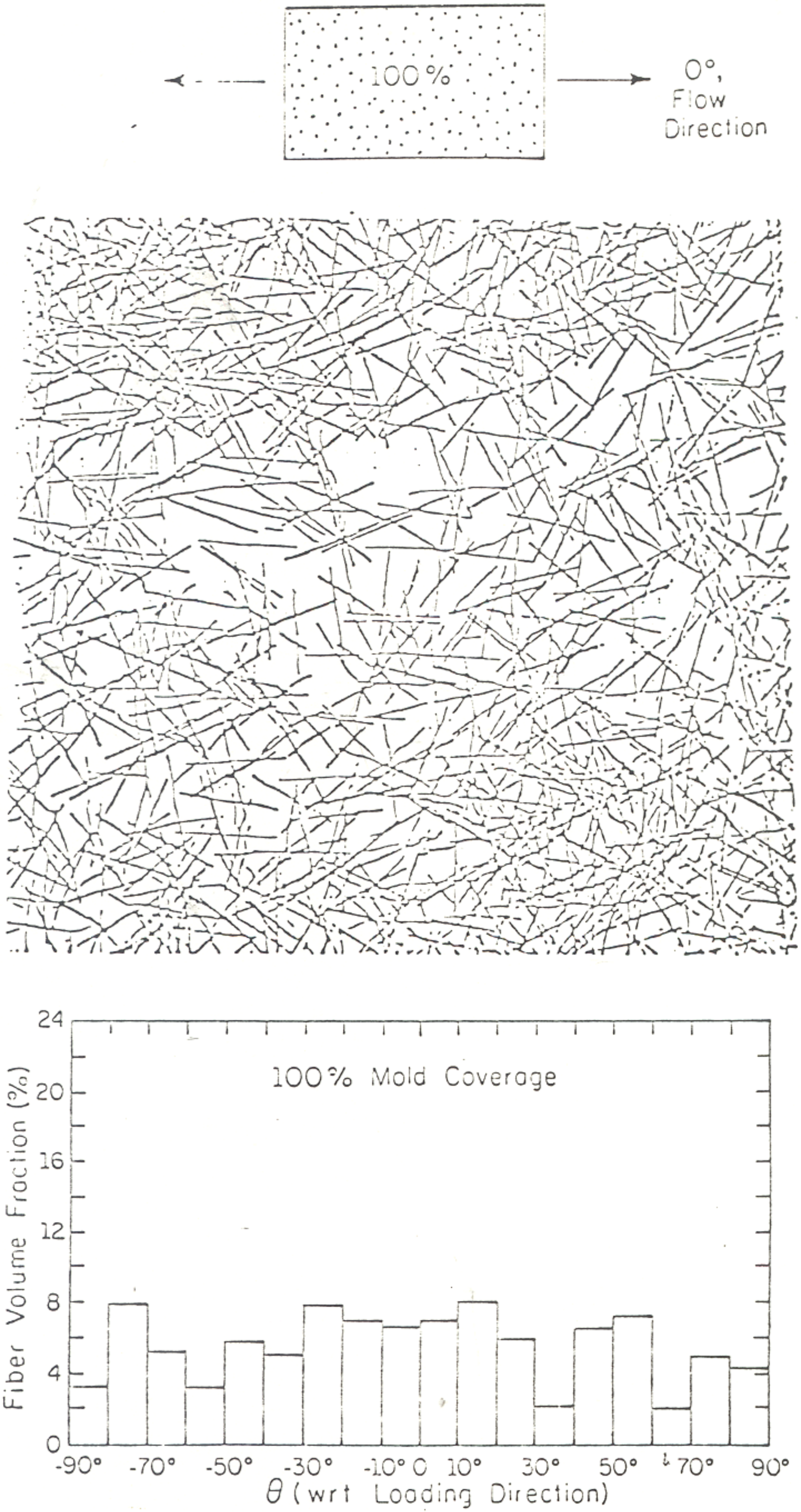
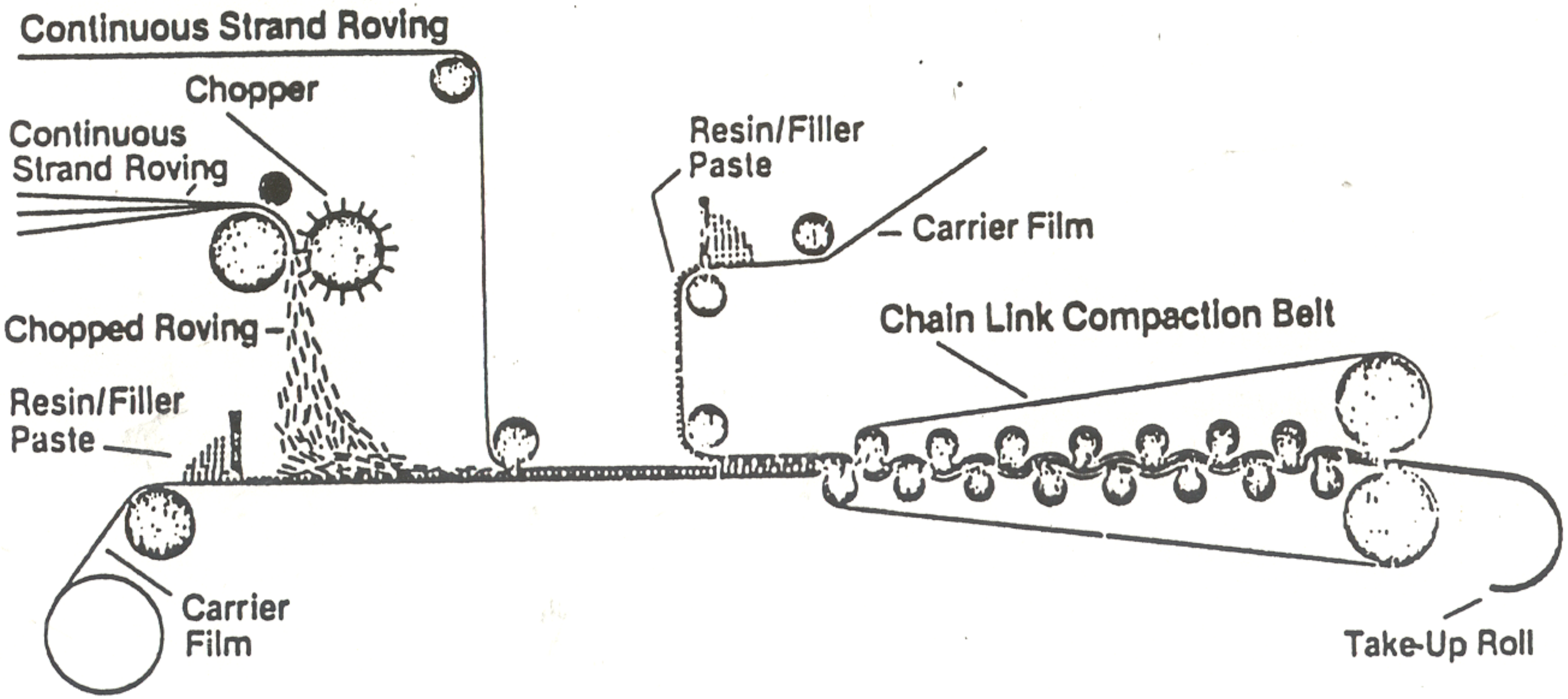


Figure 4.6 Radiograph of the Fibers and Fiber Orientation Histogram for 100 Percent Mold Coverage.

SMC-C/R Machine



Critical Issues

Mechanical Property Control

Modulus and Tensile Strength vary greatly
Inherent inhomogemneity in the material
Fiber Orientation

Surface Finish

develop porosity, surface waviness, sink marks
use low profile resins,
adding fiber free coating to the part

Cycle Time

time it takes to produce a part from from a single mold and press.
Controls cost of tooling and production equipment.

Mold design

related to preceding issues.
Construction of molds expensive so analytic tools useful

Process Automation

Reduction of human effort required
devices to load and unload - goal is to reduce labor cost

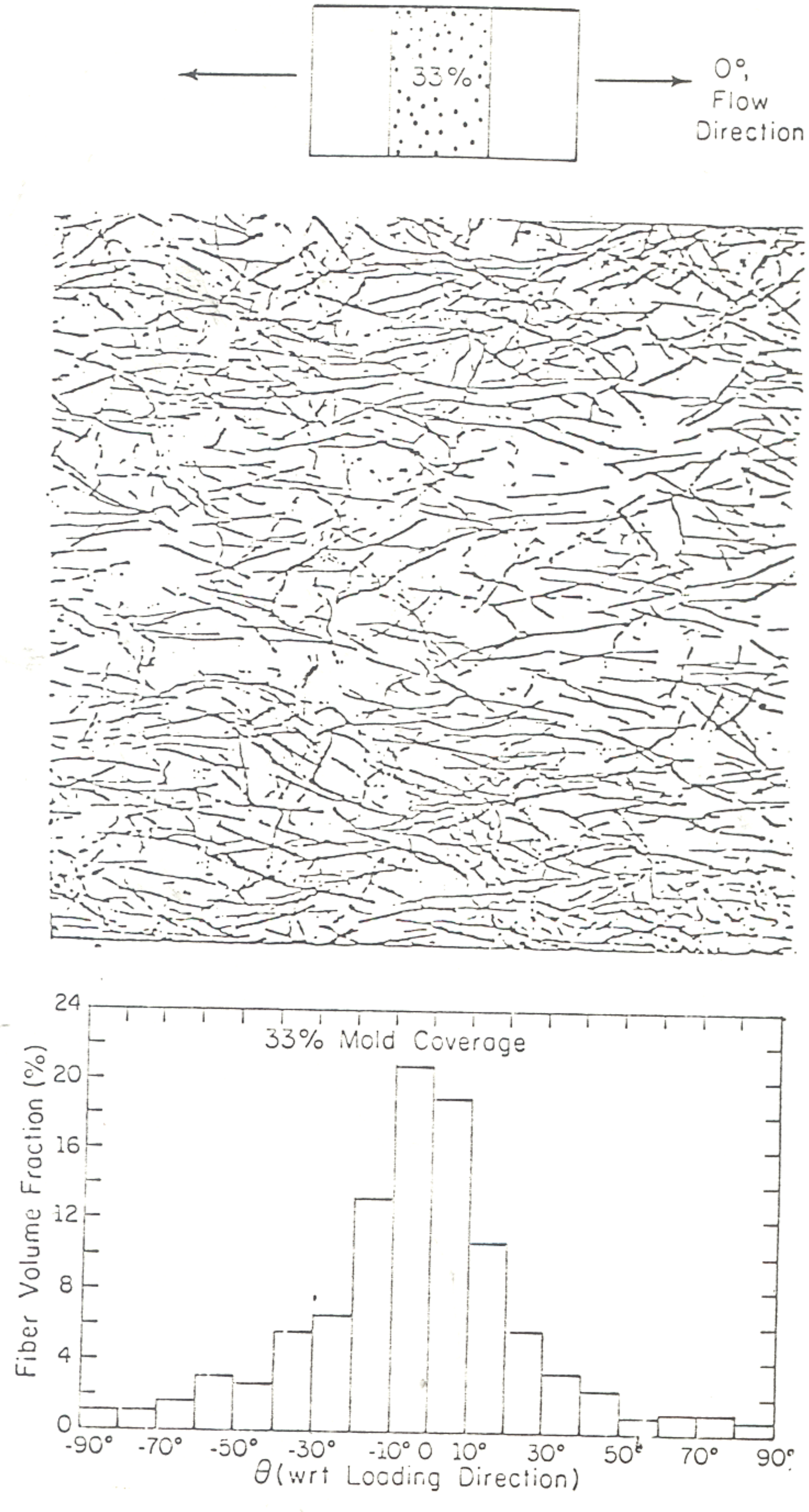
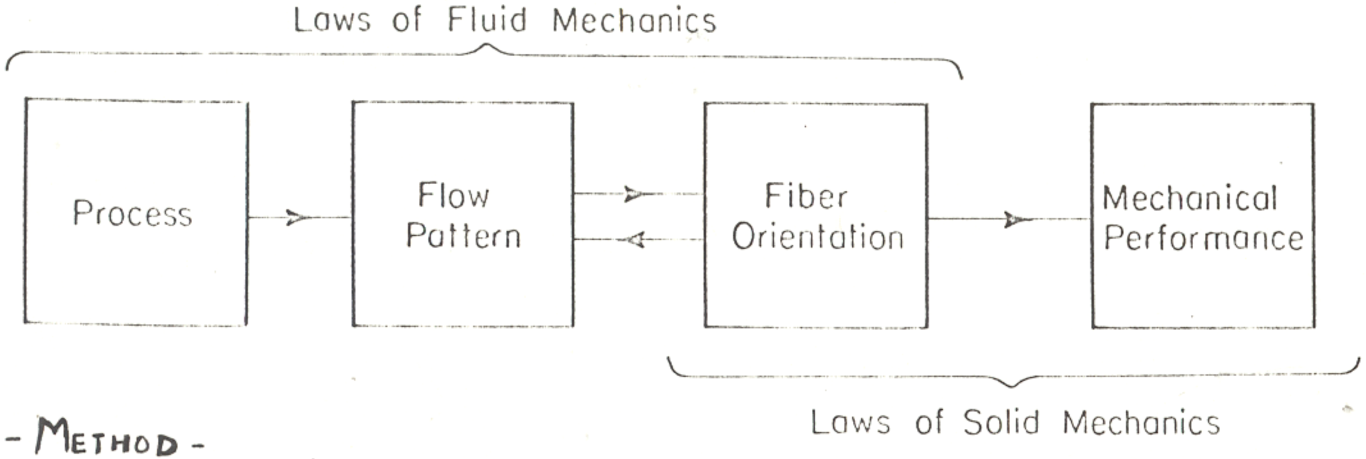


Figure 4.9 Radiograph of the Fibers and Fiber Orientation Histogram for 33 Percent Mold Coverage.



- METHOD -

- MOLD FILLING SIMULATIONS
- FIBER ORIENTATION PREDICTIONS
- MECHANICAL PROPERTY PREDICTIONS

Stages in the compression molding process

1. Material Preparation:

Molding compound or a prepreg is made.

This may involve compounding a resin, combining a resin with fibers, etc.

Controls the rheological properties of the compound and the bonding between fibers and resin.

2. Pre-fill Heating

to speed up processing.
May be done outside the mold to using dielectric heating.
With SMC heating takes place after the compound is placed in the mold

3. Mold Filling

Begins when the polymer begins to flow and ends when the mold is full.
Although the flow is modest, it controls the orientation of the reinforcing fibers.
In laminates there is no flow and hence this stage is absent.

4. In-mold curing

Describes the stage that follows mold filling where the part cures in the mold.

In-mold curing converts the polymer from a liquid into a solid.

Interaction between heat transfer and curing.

5. Part Removal and Cool-Down

Residual stresses. One source of residual stress is the difference in thermal expansion between different positions in the part.

Distortions will arise as the part cools down.

The temperature distribution and the rate of coling are important to determine how these stresses can be relaxed.

FLOW MODELS FOR THIN CAVATIES

Objective

To predict the mold filling pattern starting with the initial charge shape and finishing with the full mold.
Useful information

will it fill the mold before it cures
knit line locations,
velocity and pressure distributions.

Lay flat approximation

The part is conceptually "unfolded"

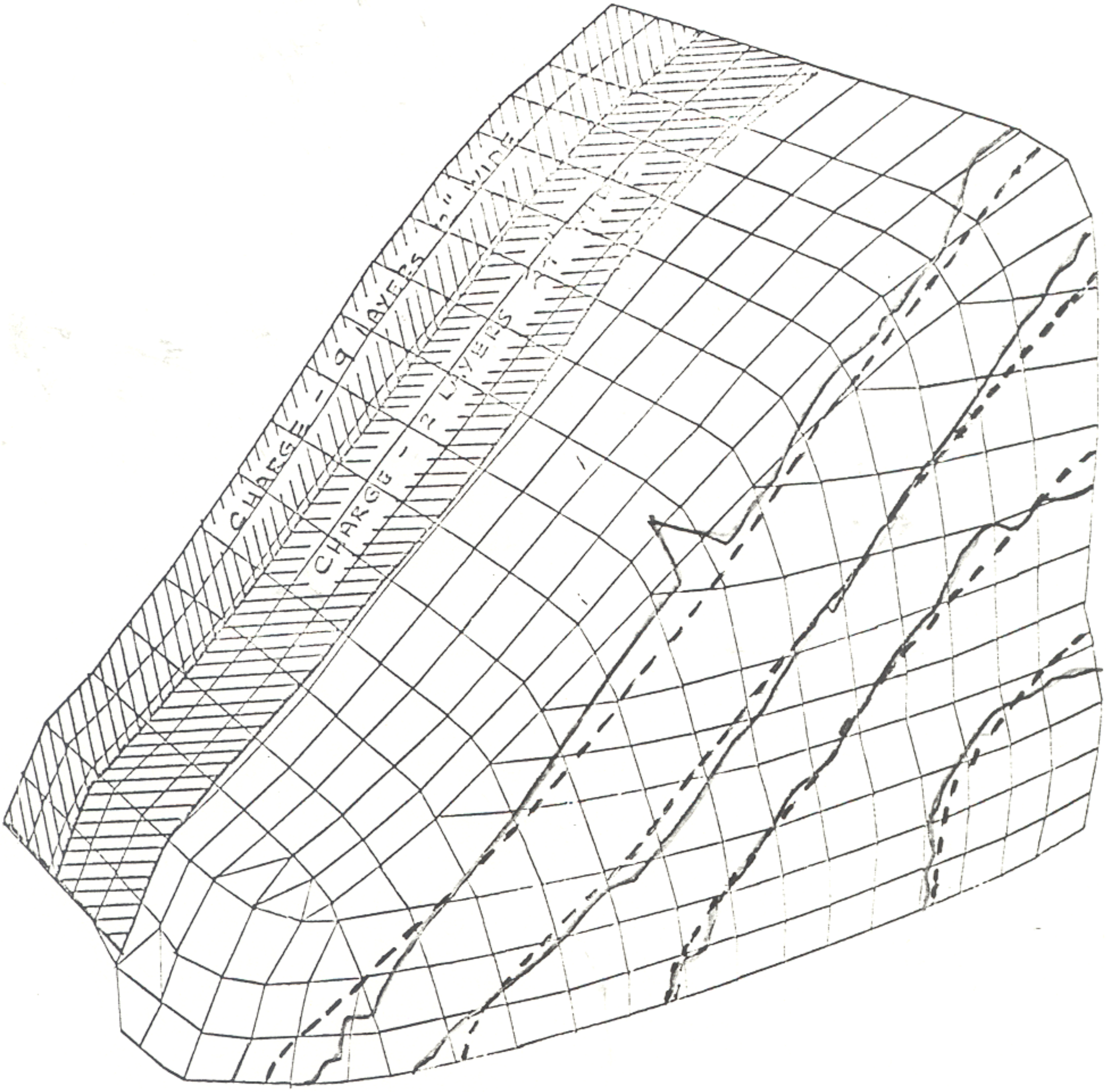
Transforms three dimensional shape into equivalent flat part

Assumptions

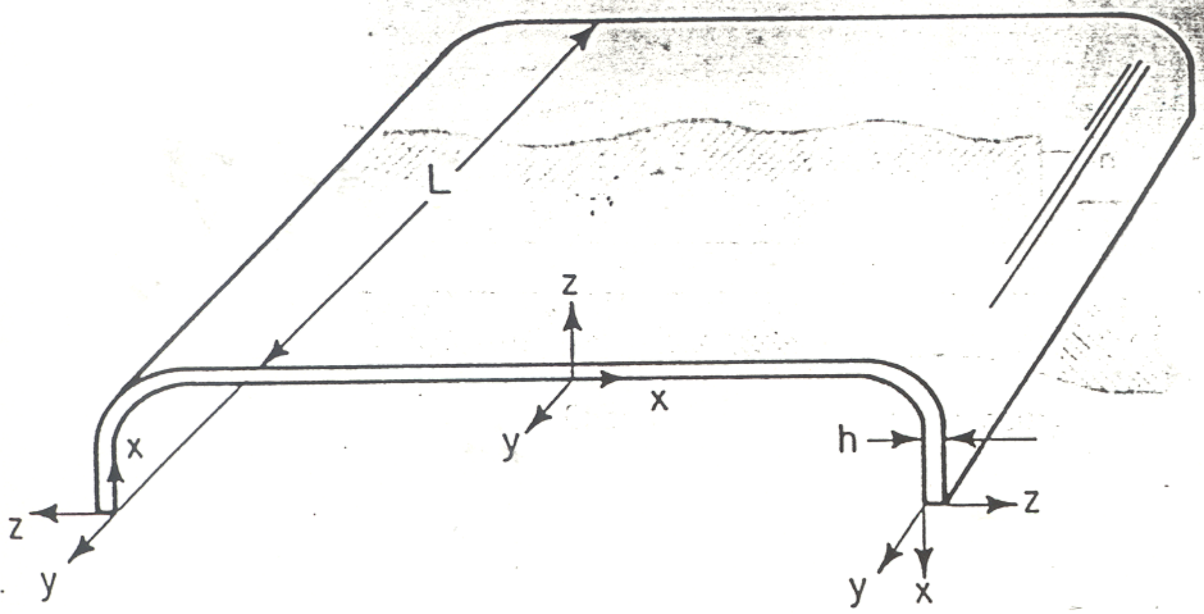
negligible inertia
inelastic isotropic model for rheology of the compound
assume temperature field known
viscosity function of temp. and hence position

NAVISTAR AIR DEFLECTOR –

FILL PATTERN



——— EXPERIMENTAL
- - - - PREDICTED



2 Coordinate system and nomenclature for compression mold filling analysis.

Figure 1 Example of thin part which can be treated by the Generalized Hele-Shaw flow model.

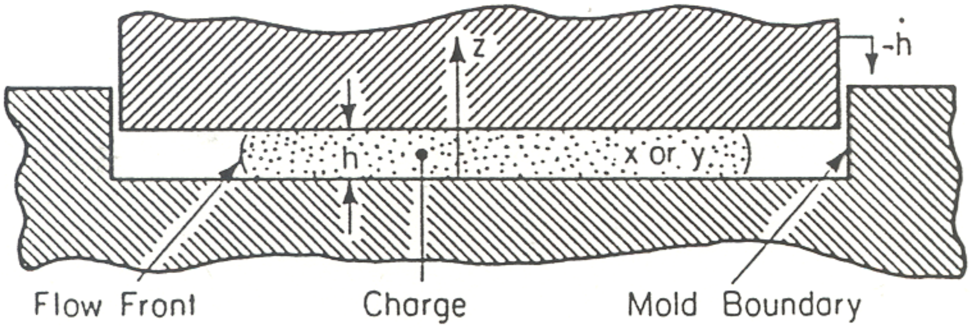


Figure 2 Coordinate system and nomenclature for compression mold filling analysis.

L characteristic dimension in x-y plane

$w \sim s$ s = speed of closing

$u \sim s\frac{L}{h}$

$v \sim s\frac{L}{h}$

For $h \ll L$, the flow is planar

GAPWISE AVERAGE VELOCITIES

$$\bar{u}(x,y) = \frac{1}{h}\int_0^h u(x,y,z)\,dz$$

$$\bar{v}(x,y) = \frac{1}{h}\int_0^h v(x,y,z)\,dz$$

EQUATIONS OF MOTION

$$\frac{\partial P}{\partial x} = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}$$

$$\frac{\partial P}{\partial y} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}$$

TWO WAYS TO SIMPLY

(1) LUBRICATION APPROXIMATION

ONLY OUT-OF-PLANE SHEAR STRESSES IMPORTANT

$\frac{\partial \tau_{zx}}{\partial z}$, $\frac{\partial \tau_{zy}}{\partial z}$ DOMINATE

This Leads to:

Generalized Hele-Shaw (GHS) Model.

(2) SQUEEZING FLOW MODEL

A thin Lubricated layer near the wall makes $\frac{\partial \tau_{zx}}{\partial z}$ and $\frac{\partial \tau_{zy}}{\partial z}$ very small.

HENCE DOMINATING STRESSES ARE τ_{xx}, τ_{xy} and τ_{yy}

LUBRICATING FLOW AND SQUEEZE FLOW RERRESENT TWO EXTREME CASES OF THIN COMPRESSION MOLDING FLOWS.

GHS FLOW MODEL

$$\frac{\partial u}{\partial x} \sim \frac{u_c}{L} \qquad \frac{\partial u}{\partial z} \sim \frac{u_c}{h}$$

FOR INELASTIC FLUID

$$\frac{\partial T_{xx}}{\partial x} \sim \eta \frac{u_c}{L^2}$$

$$\frac{\partial T_{zx}}{\partial z} \sim \eta \frac{u_c}{h^2}$$

EQUATIONS OF MOTION

$$\frac{\partial P}{\partial x} = \frac{\partial T_{zx}}{\partial z}$$

$$\frac{\partial P}{\partial y} = \frac{\partial T_{zy}}{\partial z}$$

Heiber and Shen have shown

$$\bar{u} = -\frac{S}{h}\frac{\partial p}{\partial x}$$

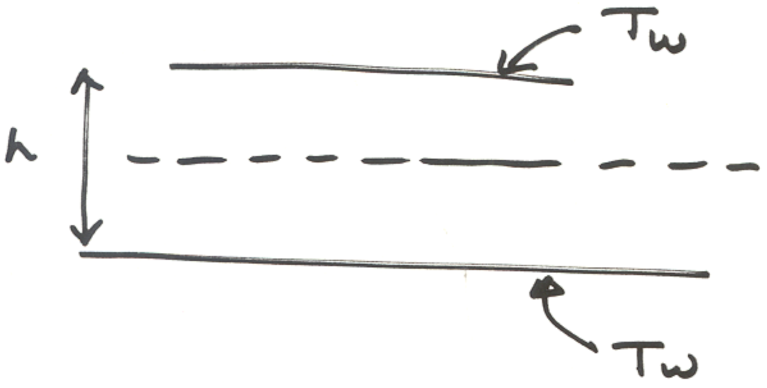
$$\bar{v} = -\frac{S}{h}\frac{\partial p}{\partial y}$$

where $$S = \int_0^h \frac{(z-\lambda)^2\,dz}{\eta(z)}$$

λ is the value of z where

τ_{zx}, τ_{zy} vanish

If



$\lambda = \frac{h}{2}$

Substitute $\bar{u}$ and $\bar{v}$ in

Integrated continuity

$$\frac{\partial}{\partial x}\left(S\,\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(S\,\frac{\partial P}{\partial y}\right) = -S$$

Solve for $P(x,y)$

B. C $\qquad P = 0$ ON THE FRONT

$\qquad \dfrac{\partial P}{\partial n} = 0$ At Mold Boundary

$$u(x,y,z) = \frac{\partial P}{\partial x}(x,y) \int_0^z \frac{(z-\lambda)\,dz}{\eta}$$

$$v(x,y,z) = \frac{\partial P}{\partial y}(x,y) \int_0^z \frac{(z-\lambda)\,dz}{\eta}$$

$$\lambda = \frac{\int_0^h \frac{z\,dz}{\eta}}{\int^h dz/}$$

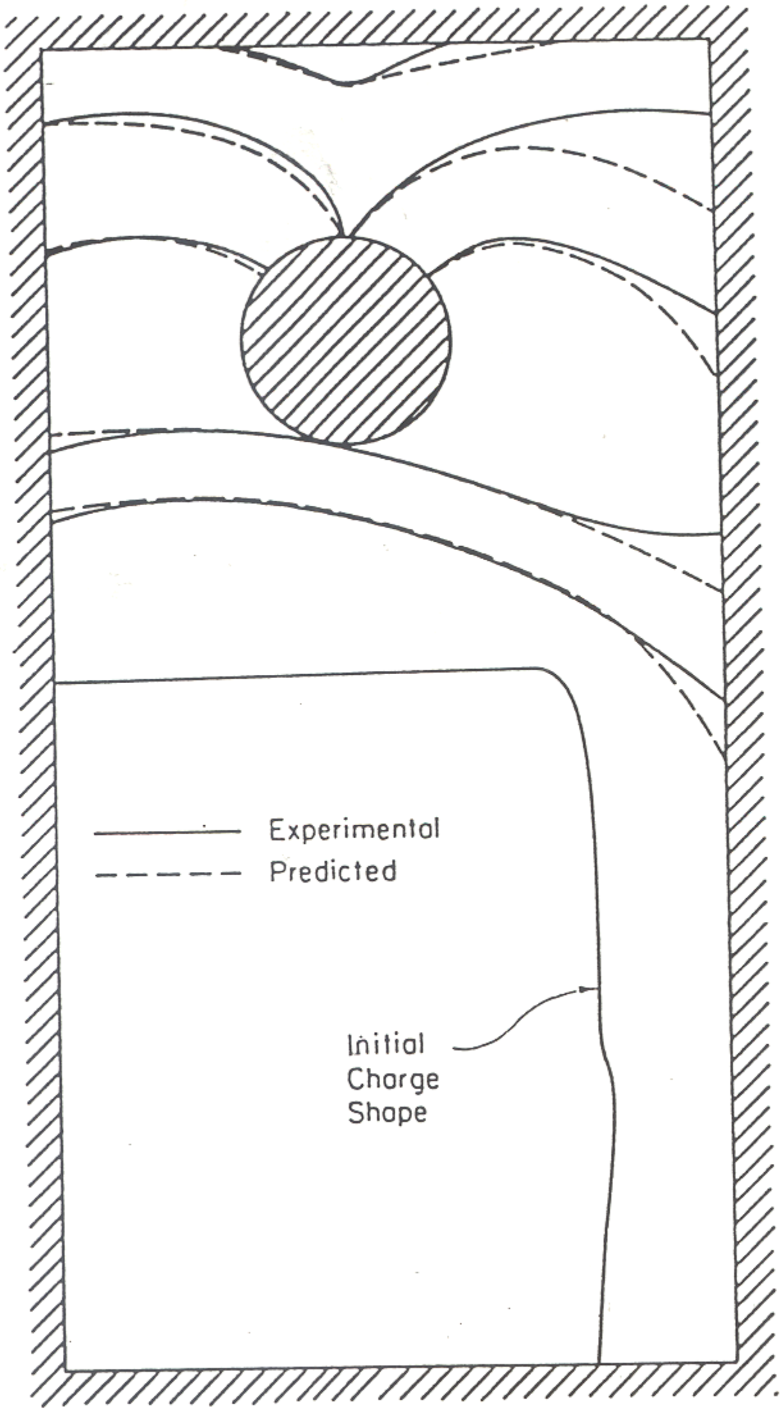
Special Case: Newtonian - isothermal.

$$\bar{u} = \frac{h^2}{12\mu}\left(-\frac{\partial p}{\partial x}\right)$$

$$\bar{v} = \frac{h^2}{12\mu}\left(-\frac{\partial p}{\partial y}\right)$$

$$\boxed{\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = -\frac{12\mu}{h^3}S}$$

As the flow domain is changing it introduces time dependenee of Pressure and velocity



igure 6 Calculated and experimental flow front positions for filling mold with obstacle (T. A. Osswald and C. L. Tucker, unpublished research results).

Limitations: of G+IS

(1) $\underline{h << L}$

(2) no slip along the vertical walls

make $\frac{\partial \tau_{xy}}{\partial y}$ or $\frac{\partial \tau_{xy}}{\partial x}$ large

on the edges

(3) $\frac{\partial \tau_{zx}}{\partial z}$ $>>$ In plane stresses

$\frac{\partial \tau_{zy}}{\partial z}$ $\quad \frac{\partial \tau_{xx}}{\partial x}, \frac{\partial \tau_{yx}}{\partial y}, \frac{\partial \tau_{yx}}{\partial x}.$

Near the wall this is true

In the midplane?

$$\frac{\eta_w L^2}{\eta_c h^2} >> 1$$

For it to be valid!

LUBRICATED SQUEEZING FLOW

$$\frac{\partial T_{xz}}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial u}{\partial z} = 0$$

$$u\,(x, y) \quad \rightarrow \quad \bar{u} = u$$

$$\frac{\partial P}{\partial x} = \frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{yx}}{\partial y}$$

$$\frac{\partial P}{\partial y} = \frac{\partial T_{xy}}{\partial x} + \frac{\partial T_{yy}}{\partial y}$$

Flow is usually

biaxial extensional

pure shear flow

FOR ISOTHERMAL NEWTONIAN CASE

$$\frac{\partial p}{\partial x} = \mu \nabla^2 u$$

$$\frac{\partial p}{\partial y} = \mu \nabla^2 v$$

and $$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \frac{s}{h}$$

h = constant at a given time.

velocity normal to the boundary is zero.

ON THE FREE FLOW FRONT

$$\sigma_{nn} = 2\mu \frac{\partial v}{\partial n} - p = 0$$

where p = pressure inside the charge. which is <u>not equal</u> to pressure outside the charge.

CURING BY <u>ADDITION</u> - <u>POLYMERIZATION</u>

ADVANTAGES: SHARPER TRANSITION FROM LIQUID TO GEL

MOLD FILLING CAN BE COMPLETED BEFORE CURING STARTS

IN RIM CURE BY CONDENSATION - REACTION

HEAT TRASFER AND CURING

CURE BY THERMAL ACTIVATION

ALSO: CURING IS EXOTHERMIC

HEAT TRANSFER PLAYS DUAL ROLE

(i) HEAT MUST BE CONDUCTED ~~INO~~ INTO THE POLYMER TO BEGIN CURE

(ii) HEAT FROM CURING MUST BE CONDUCTED OUT BEFORE IT BURNS THE POLYMER

HEAT TRANSFER AND CURING

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + \underbrace{\rho Q_T \frac{\partial c}{\partial t}}_{\text{heat generated per unit vol.}}$$

$$\frac{\partial c}{\partial t} = f(c, T)$$

$$\frac{dc}{dt} = (d_1 + d_2 c^m)(1 - c)^n$$

$$d_1 = a_1 e^{-b_1/RT}$$

$$d_2 = a_2 e^{-b_2/RT}$$

a_1, b_1, a_2, b_2, m, and n

R gas constant

T absolute temp.

HEAT TRANSFER DURING MOLD FILLING

$$\rho C_p \frac{DT}{Dt} = K \frac{\partial^2 T}{\partial z^2}$$

$T = T_0$ at $t = 0$

$T = T_w$ at $z = h$

$z = 0$

$$\xi = \frac{z}{h(t)}$$

$$\rho C_p \frac{\partial T}{\partial t} = \frac{K}{(h(t))^2} \frac{\partial^2 T}{\partial \xi^2}$$

Classical Conduction problem.