

# The Effect of Side Constraint in Rolling Compaction of Powders

Wenhai Wang<sup>1</sup>, John C. Cunningham<sup>2</sup>, and Antonios Zavaliangos<sup>1</sup>

<sup>1</sup> Drexel University,  
Department of Materials Science and Engineering,  
Philadelphia, PA 19104

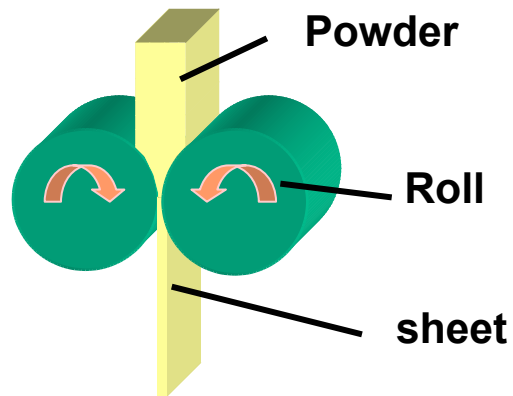
<sup>2</sup> Merck & Co, Inc., West Point, PA 19486



Funding provided by NSF –CMS 0100063



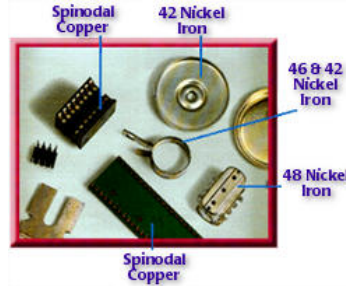
# Powder Roll Compaction



Roll compaction refers to the **continuous** compaction of powders by roll mills.

The powder is usually delivered by feed screw to rolls and densified by the **pressure** and **shear force**

**Metal:**



**Pharmaceutical:**



**Chemical:**



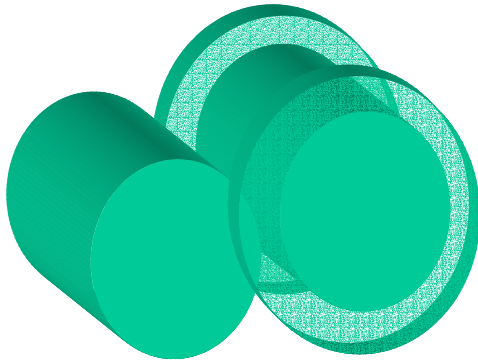
**Food:**



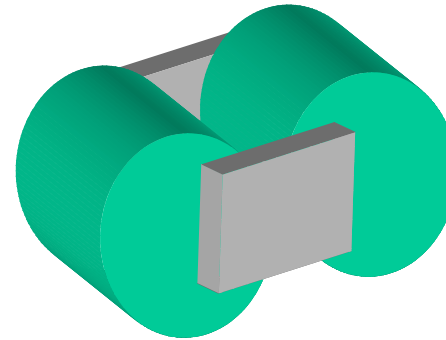
Figures copied from <http://www.fitzmill.com>  
and <http://www.ametekmetals.com>

# Side Constraints

**Roll with side ring**

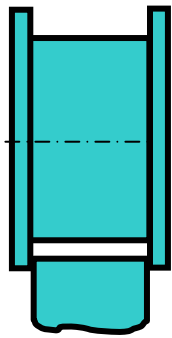


**Roll with stationary sidewall**

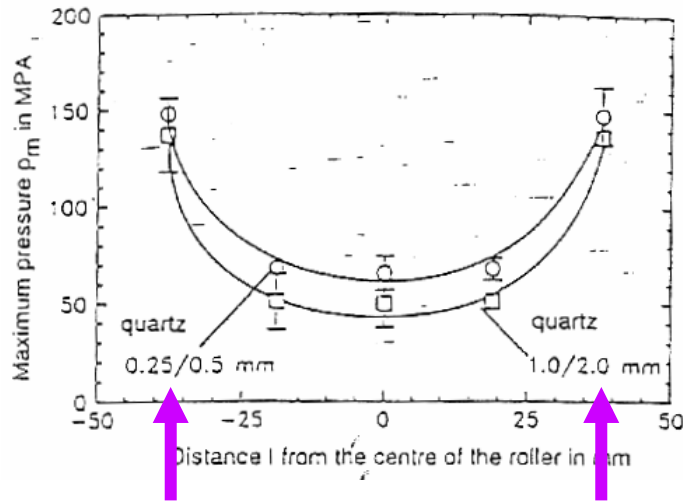


- **Side constraints are used to prevent the powder from escaping from the roll gap.**
- **Friction is unavoidable. (We never roll powder with admixed lubricants)**

# Experimental Results

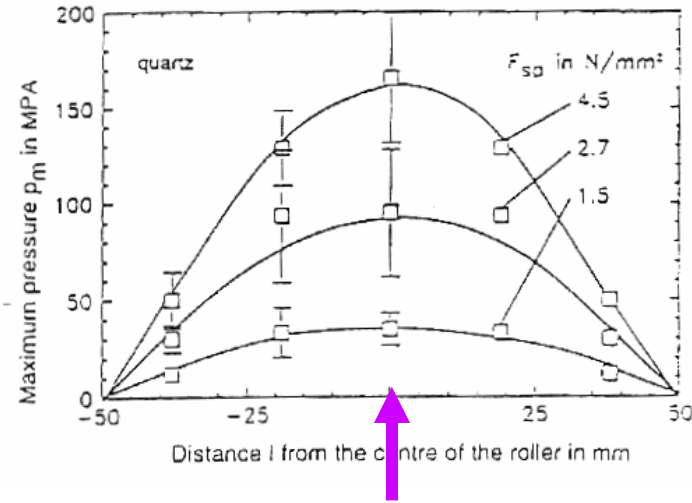


### Roll with side ring

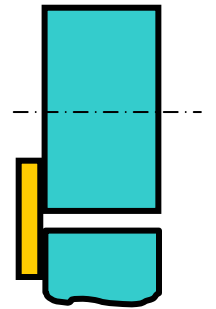


**The pressure is highest on the side.**

### Roll with stationary sidewall



**The pressure reaches maximum at center.**



# Models Development of Roll Compaction

## **1960, Johanson model**

**Johanson<sup>[2]</sup> ,Jenike , Shield <sup>[3]</sup>**

**The first model to predict behavior of the material between the rolls.**

## **1970s-1980s Slab Method**

**V.P. Katashinskii<sup>[4,5]</sup>, M.B.Stern, G.A. Vinogradov, R.T.Dec<sup>[6]</sup>, etc.**

**To predict pressure distribution and roll force in rolling process.**

## **1980s-present Finite Element Model**

**Osakada <sup>[7,8]</sup>, Mori<sup>[9]</sup>, Deshmukh<sup>[10]</sup>, Dec<sup>[11]</sup>, Zavaliangos , Cunningham, etc.**

**FEM simulations on powder compaction.**

2. J.R.Johanson, Vol. 32, ser.E, No.4, 1965, pp. 842-848.

3. A.W. Jenike & R.T.Shield, Trans, ASME, vol. 81, 1959, pp. 599-602

4. V.P. Katashinskii & M.B.Stern, Poroshkovaya Metallurgiya, No. 12(252), pp.9-13, 1983

5. V.P . Katashinskii & G.A. Vinogradov, Poroshkovaya Metallurgiya, No. 3(159), pp.31-36, 1976

6. R.T.Dec, Proceedings Inst. Briquetting and Agglomeration, Vol. 22, 1991, pp. 207-218

7. Osakada, Nakano, Mori, Int. J. Mech. Sci., 24-8(1982), 459-468

8. K.Mori, K. Osakada, Int. J. Mech. Sci. 29 (1987), 229

9. A.R. Deshmukh, T.Sundararajan, R.K.Dube, Bhargava, J. of Mate. Proc. Tech. 84(1998) 56-72

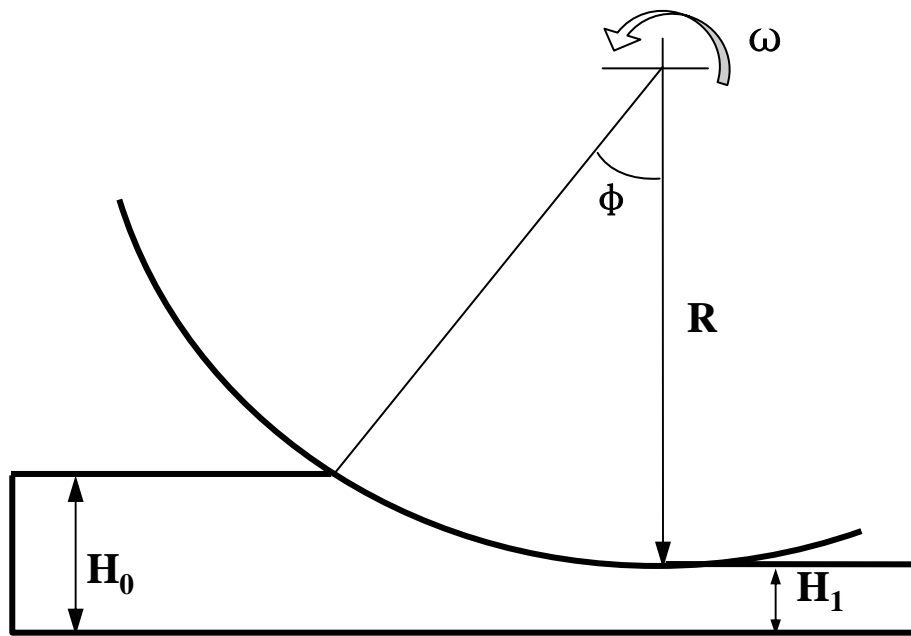
10. K.Mori, O.Ebihara, Advanced Tech. of Plast., Vol 2, Proceedings of 6th ICTP, Sept, 19-24,1999

11. Roman T. Dec, Antonios Zavaliangos, John C. Cunningham, Powder Technology 4642, 2002

# Objectives

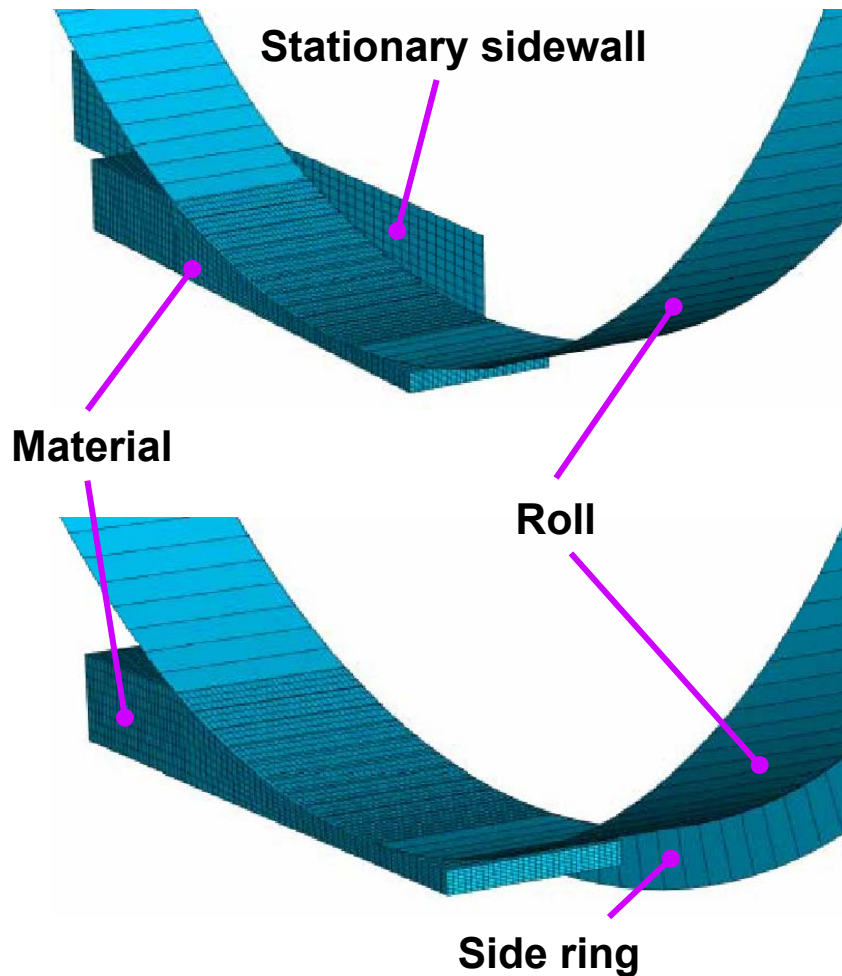
- **Explore the nature of density inhomogeneity.**
- **Evaluate the two kinds of constraint systems using FEM analysis.**

# Simulated Geometry



**$R$**  = 200 mm  
 **$H_0$**  = 12.06 mm  
 **$H_1$**  = 4 mm  
 **$\phi$**  = 20°  
 **$\omega$**  = 0.6 rad

# 3D FEM Implementation



- **ABAQUS EXPLICIT;**
- **One-fourth of the geometry due to symmetry (an approximation);**
- **16800 3D 8-noded hexahedral elements;**
- **Roller is modeled with an analytical rigid surface;**

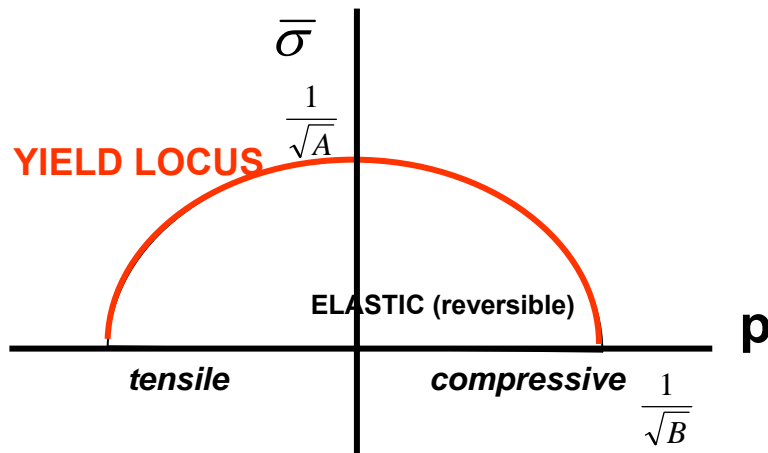


## 3D FEM Implementation (cont.)

- **Adaptive remeshing is applied;**
- **Coulomb friction is assumed upon the contact interfaces;**
- **Eulerian inflow and outflow boundary condition are implemented at the ends of the rolled specimen;**
- **Mass scaling is employed to improve computational efficiency;**
- **Simulation ends when steady state is achieved.**

# Constitutive models for Porous Materials

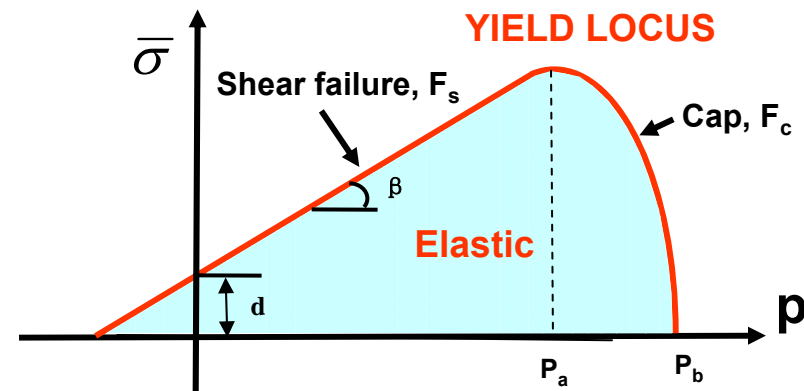
## Ellipse Model



$$\Phi(\bar{\sigma}, p, D) = A(D)\bar{\sigma}^2 + B(D)p^2 - 1 = 0$$

- $\bar{\sigma}$  equivalent stress
- $P$  hydrostatic pressure
- $D$  relative density

## Drucker-Prager Model



Shear failure region:

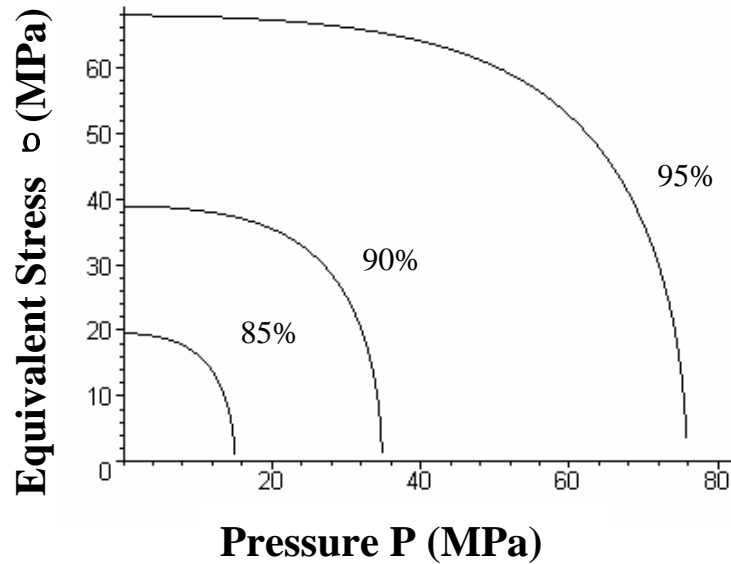
$$F_s = \bar{\sigma} - p \tan \beta - d = 0$$

Cap region:

$$F_c = \sqrt{(p - p_a)^2 + (R\bar{\sigma})^2} + R(d + p_a \tan \beta) = 0$$

- D-P model is more appropriate but numerical implementation in ABAQUS has problems;
- Gurson's model is chosen (overestimates loads).

# Gurson's Model



where  $\bar{\sigma}$  is the effective Mises

stress:  $\bar{\sigma} = \sqrt{\frac{3}{2} S \bullet S}$  ;

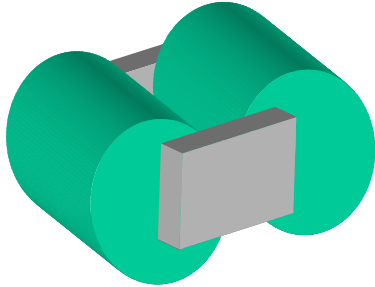
$S$  is the deviatoric part of the  
cauchy stress tensor ;

$P$  is the hydrostatic pressure

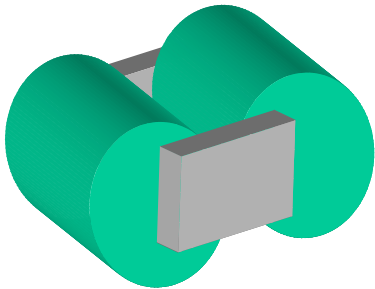
$f$  is the porosity of the material.

$$\Phi(\bar{\sigma}, P, f) = \left(\frac{\bar{\sigma}}{\sigma_Y}\right)^2 + 2q_1 f \cosh\left(-q_2 \frac{3P}{2\sigma_Y}\right) - (1 + q_3 f^2) = 0$$

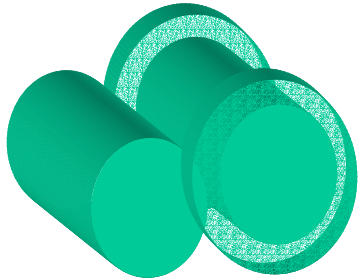
## Cases Studied



**Stationary sidewall with  $\mu = 0.4$  at powder/wall and powder/roll interface;**

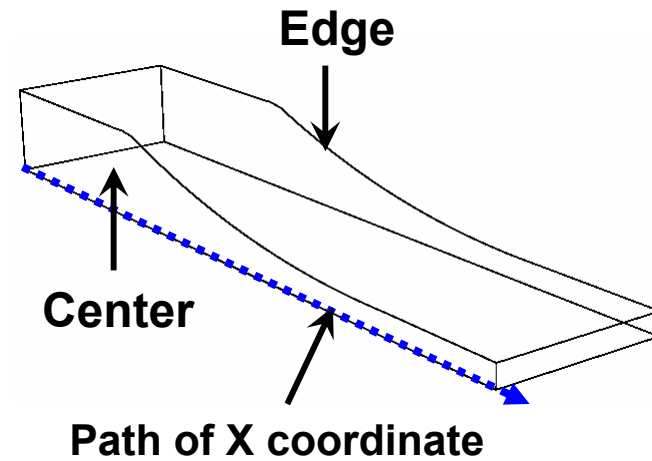
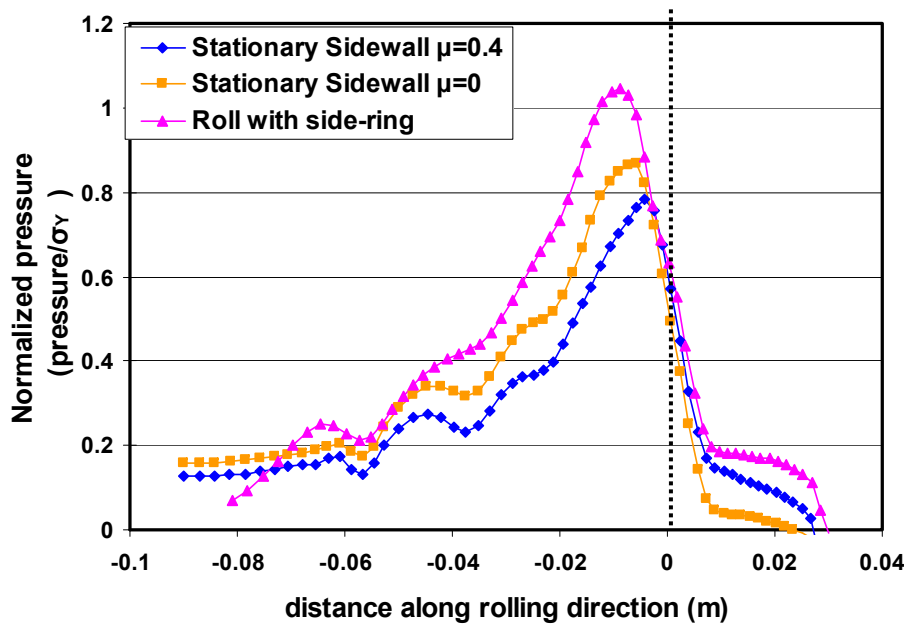


**Stationary sidewall with  $\mu = 0$  at powder/wall and  $\mu = 0.4$  at powder/roll interface;**



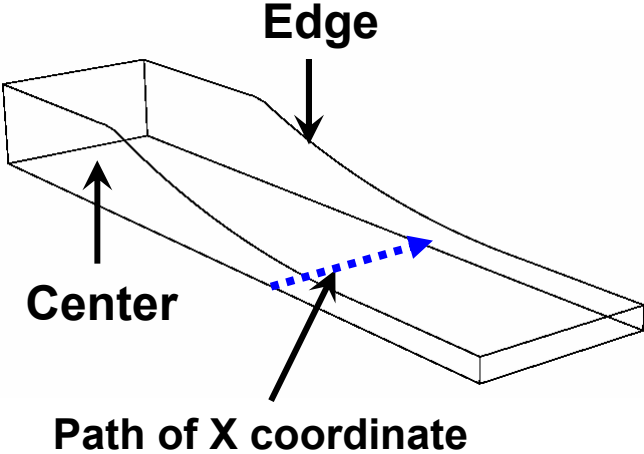
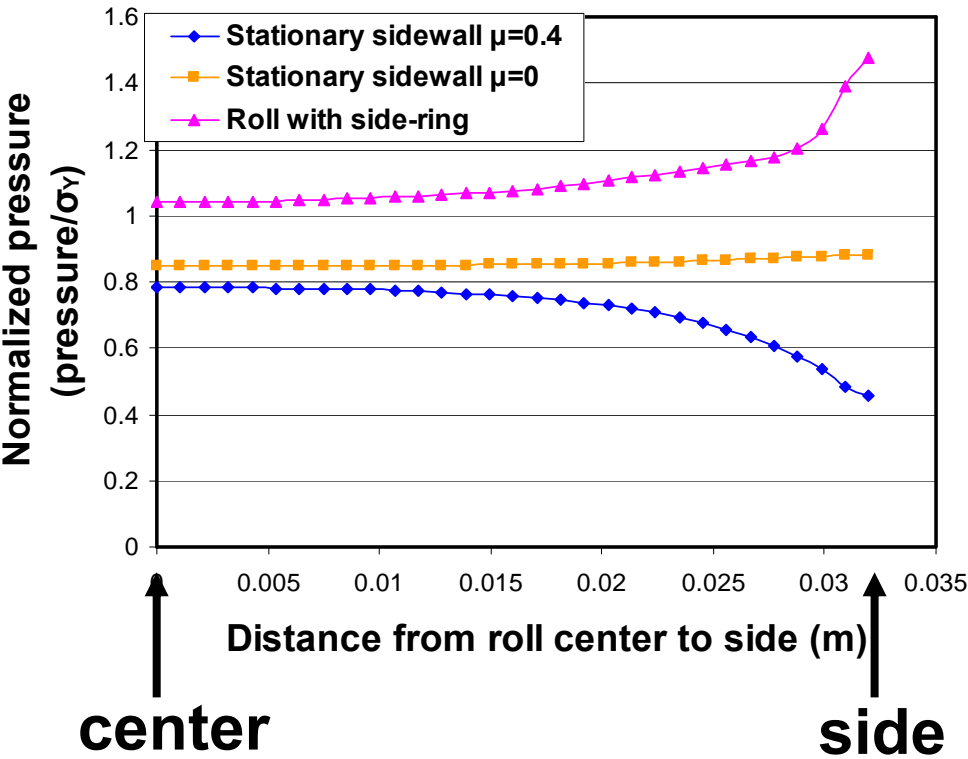
**Roll with side ring, with  $\mu = 0.4$  everywhere.**

# Pressure Distribution Along Roll Direction



**Roll pressure rises to a maximum just before the exit.**

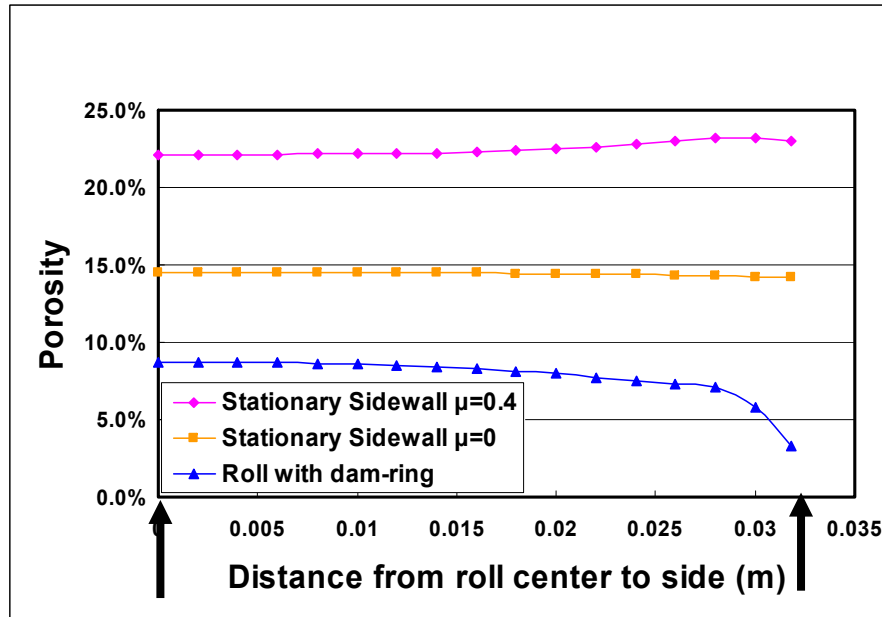
# Pressure Distribution along Roll Width



***Inhomogeneous*** pressure distribution along roll width for all cases with  $\mu \neq 0$ .

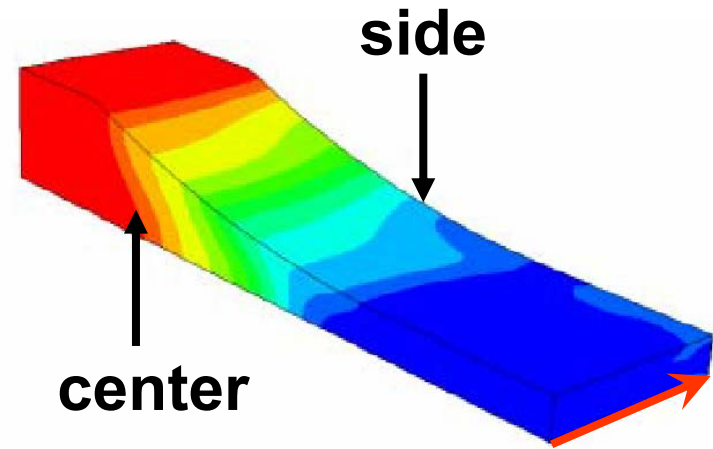


# Porosity Distribution along Roll Width



Center

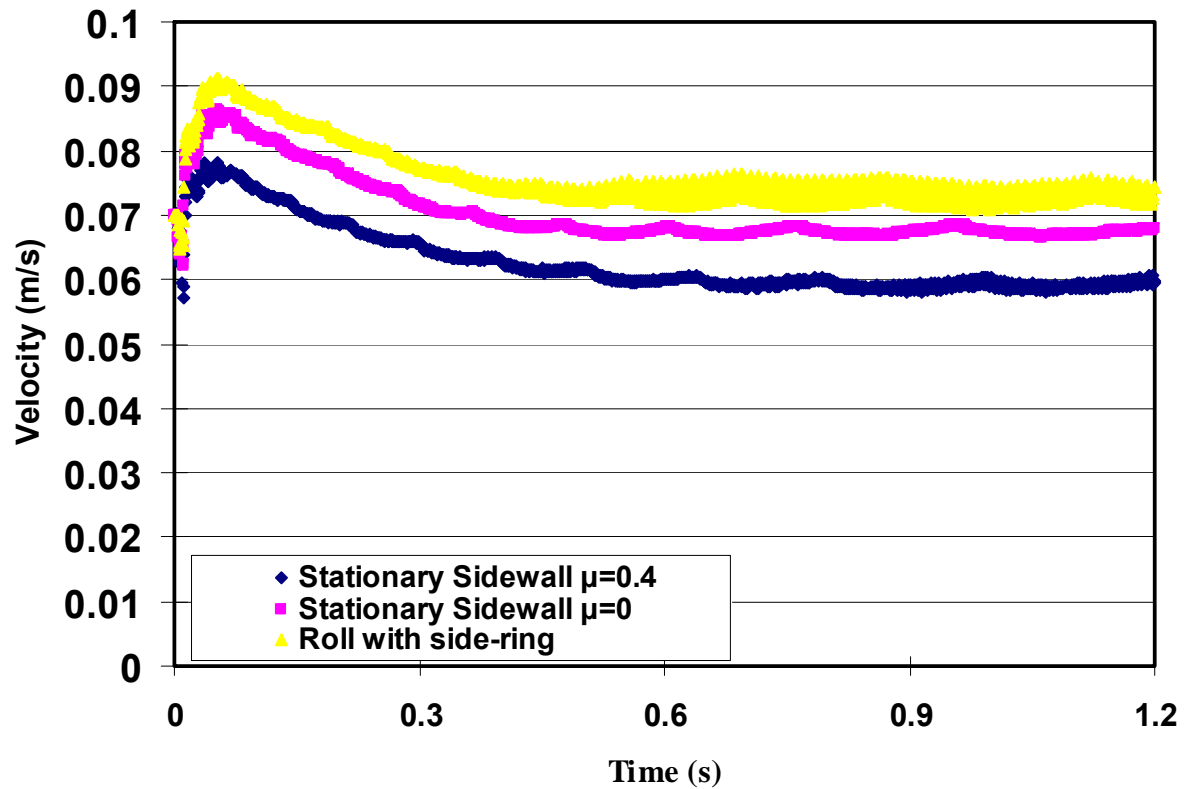
side



**Porosity** <sub>roll with "dam-ring"</sub> < **Porosity** <sub>roll with "stationary sidewall"</sub>

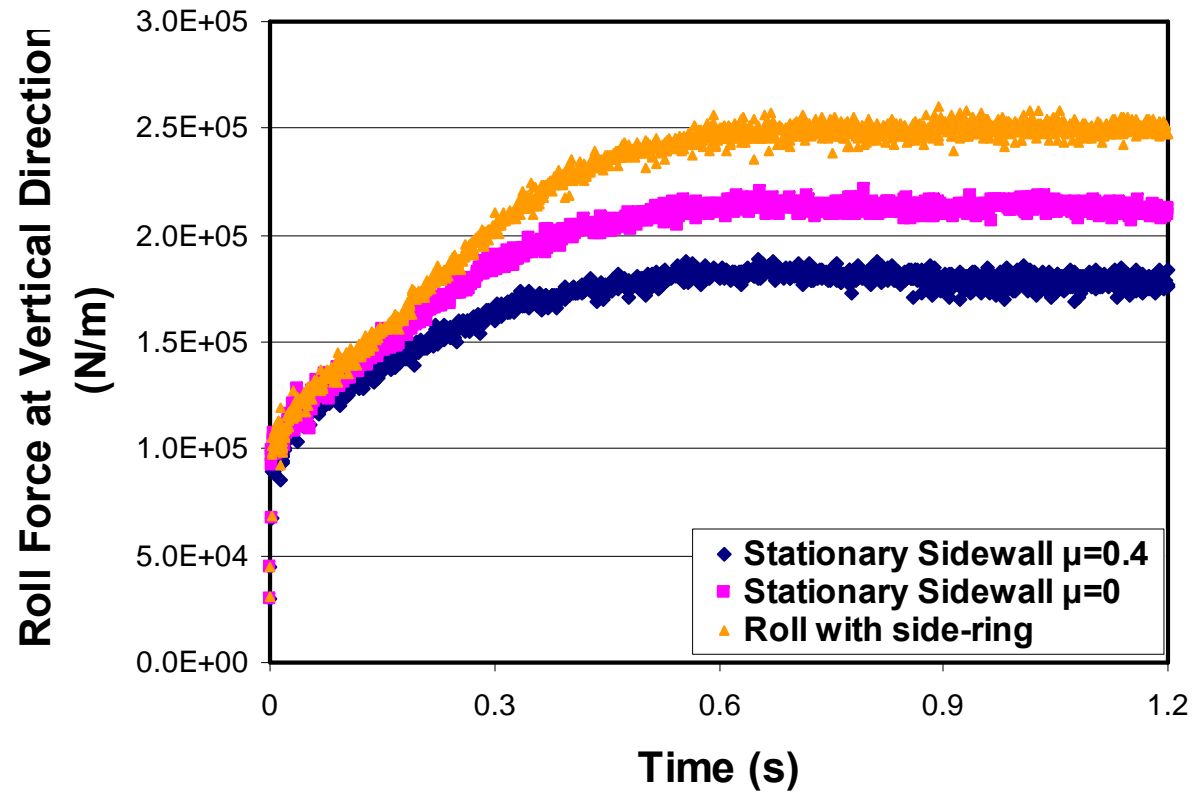


# Entrance Velocity



**At the same  $\omega$ , roll with side ring has higher throughout.**

# Roll Force Evolution



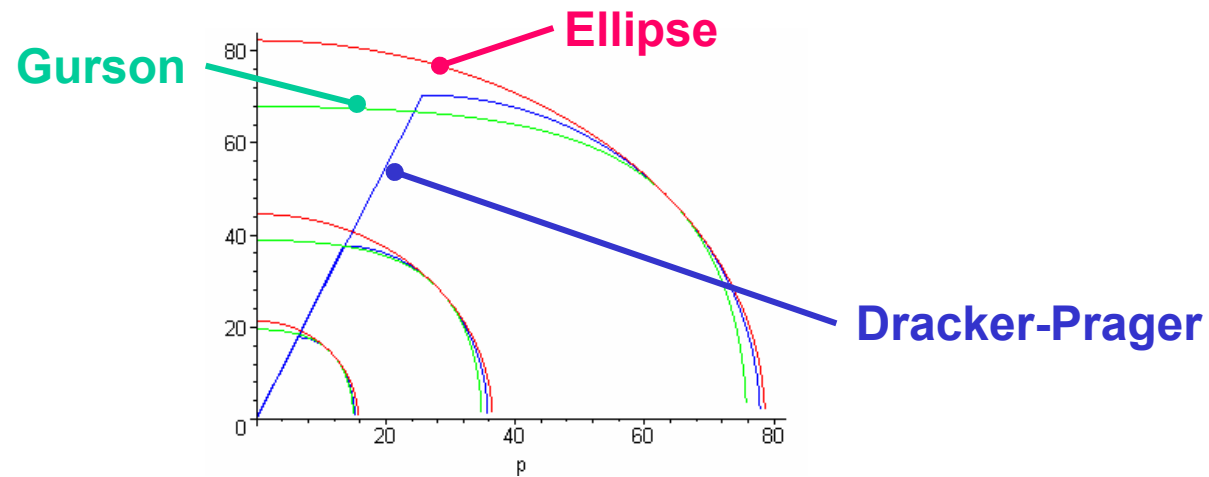
**RF<sub>2</sub> higher for side ring because the achieved density is much higher.**

# Conclusions

- **Simulation results replicates experimental trends in pressure distribution.**
- **Inhomogeneity has its origin in the friction with constraints.**
- **Side ring results a much more efficient densification, but it does not eliminate porosity variation.**
- **Minimization of the property variation requires elimination of the frictional interaction between powder and side constraint.**

# Future Work

1. More realistic constitutive models for both material and friction are needed.



2. Further verification with experiments.