Metal Forming – BSc 2024/25-1

Friction

Topics

- Tribology
- Different friction models
- Role of lubricants and requirements
- Measurement of friction

Introduction

Friction is a very complicated phenomenon, influenced by several hardly treatable parameters.

Tribology is the study of **interactions of surfaces** due to their relative motion.

The **friction is hindering the displacement** of the surfaces, and can be characterized with the force hindering the motion. During friction particles are separating the bodies and might be „welded" to other particles or the surfaces.

Wear processes occur on touching and sliding surfaces under load. These have significant influence on the forming processes. The phenomenon of **wearing causes** material loss, dimension changes and surface damage.

Damage of workpiece surfaces: production quality problem.

Damage of die surfaces: reducing the service life.

Introduction

Since 3500 B.C. in **Mesopotamia and Egypt**, lubricants were used in rotary and linear movements. Oil in metal spinning was used in 600 B.C.

The studies of **Leonardo da Vinci** on friction and wear in the 14th and 15th centuries has founded the modern tribology by the understanding of basic mechanisms.

The research of **Hooke** in 1685 concerning rolling friction and the work of **Newton** in 1687 on viscous flow has formed the bases of lubrication mechanisms.

The first law of friction was suggested by **Amonton** in 1699.

The **Coulomb** law of friction was published in 1785, for which he was awarded the Academy of Sciences Prize.

In the 19th century **Reynolds** studied the fluid film lubrication; **Goodman** measured the thickness of the oil film in a bearing. **Stribeck** published the Stribeck curve identifying the various regimes of lubrication.

Surface velocity and pressure

Machine parts: the points of the contact surface moving with equal velocity.

Workpiece during forming: the velocity of the contact surface can be different in different positions.

The **relative velocity** of moving surfaces **is usually higher** in machines than during forming techniques.

The **pressure** between the surfaces **in forming** technologies is much higher than in bearings, it can reach **2500 MPa** or even higher.

The contact surface can undergo extensive deformation due to the high pressure. The geometry changes, and the contact area increases.

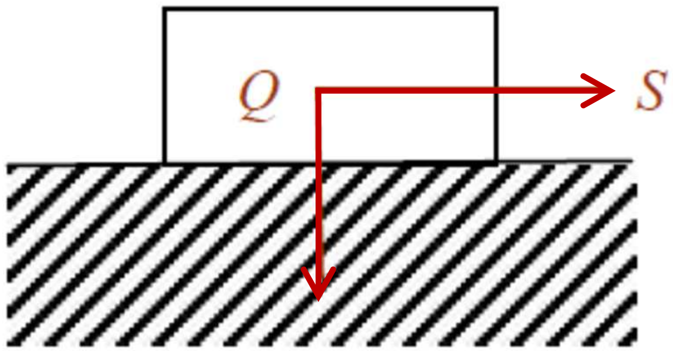
The metals surface is always covered with an **oxide layer** (hot forming), its chemical and physical **properties differ** from those of the **base metal**, and significantly affect the friction.

The **hardness of the forming die** is always notably higher than that of the workpiece, while the **dies' surface roughness** is smaller. The workpiece is going to have the shape of the die's geometry.

Friction models

Amonton-Coulomb friction

If a body is pressed with a force **Q** to an other one, then:



$S = \mu\, Q$ force is needed to move it

$$\frac{S}{A} = \mu\,\frac{Q}{A} \;\longrightarrow\; \tau = \mu\, q \qquad \mu \geq 0$$

At metal forming the max. value at sticking: $\mu_{max} = \frac{1}{\sqrt{3}} = 0.577$

For this model:

Friction is independent on the relative velocity of the bodies.

Friction is linearly proportional with the contact pressure.

Friction is independent on the direction of movement.

Friction models

Some characteristic Amonton-Coulomb friction coefficients

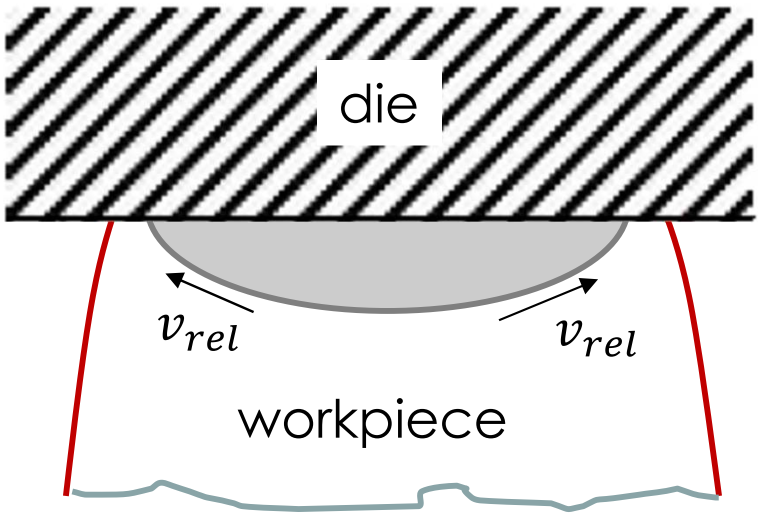
Well-lubricated bearing	0,03 or greater
Non-lubricated (dry) bearing	0,5 – 0,7
Metallic clear surfaces in vacuum	up to even 5
Comfortable walking needs	0,2 – 0,3
Shoe on sliding floor	~0,15
Ice skating	< 0,05
Knee joint	~0,02

In metal forming	**cold**	**hot**
Forging	0,05 – 0,1	0,1 – 0,2
Rolling	0,05 – 0,1	0,2 – 0,7
Drawing	0,03 – 0,1	
Sheet metal forming	0,05 – 0,1	0,1 – 0,2

Friction models

Kudo (shear) friction:

If a part of the body (grey volume) is „sticking" to the die because of the friction, the relative movement happens within the formed material. It happens when the shearing stress between the two bodies reaches the shearing flow stress:



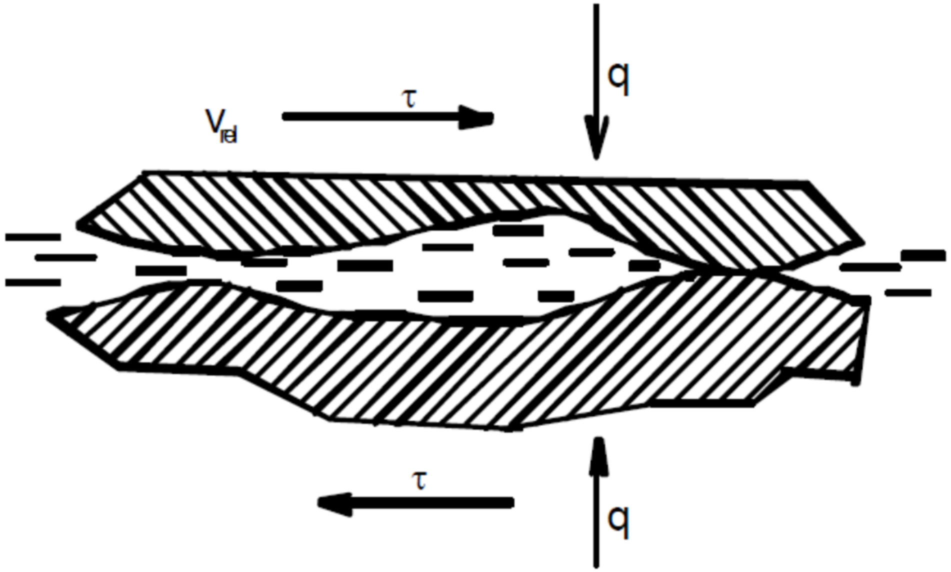
$$\tau = m\,\tau_{max} = m\,\tau_{flow}$$

$$\tau_{flow} = \frac{\sigma_{flow}}{\sqrt{3}}$$ (Mises theory)

$$\tau = m\frac{\sigma_{flow}}{\sqrt{3}} \qquad 0 \leq m \leq 1$$

Sticking happens at $m = 1$

Contact, friction



Lubricant's behavior

$$\xi = \frac{1}{\eta}\tau$$

Fluid friction

$$\tau = \eta\frac{dv}{dh}$$

μ – friction coefficient

h - gap

v – relative velocity

q – pressure

η - viscosity

$$\tau = \mu q(1+\gamma) + \eta\frac{dv}{dh}\gamma$$

$\gamma = 0..1$ - lubrication coefficient

Types of friction

Based on the lubrication state the following friction types are differentiated:

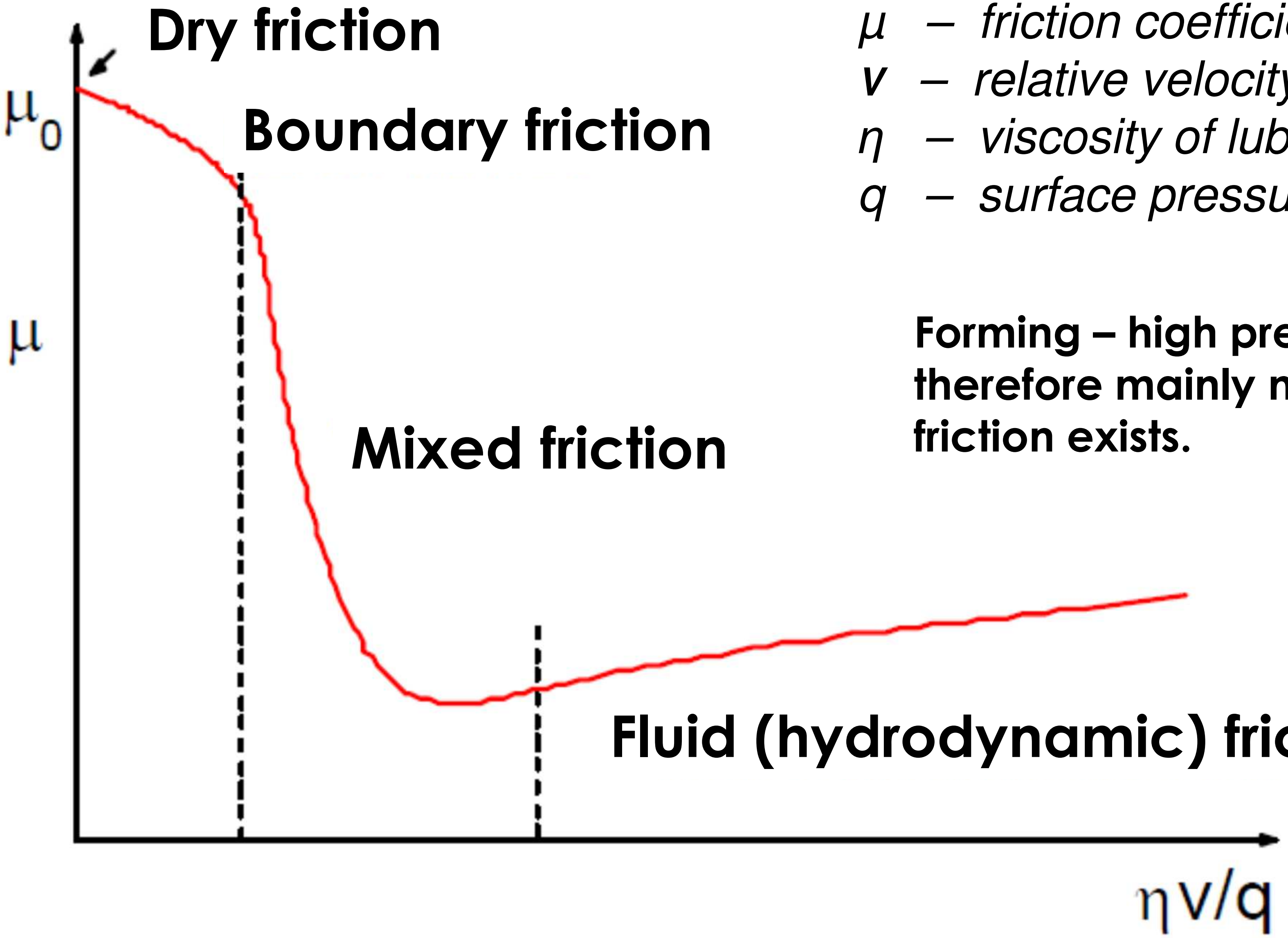
Dry friction: there is no third media between the surfaces, so metallic contact exists. In this state the friction properties are determined by the properties of the materials and the characteristics of the geometry (surface roughness).

Boundary friction: There is a thin layer of oxide or lubricant on the surfaces. The friction process is mainly determined by the properties of this layer.

Mixed friction: On some areas dry or boundary friction is characteristic, while on other areas the surfaces are separated by the lubricant.

Fluid (hydrodynamic) friction: The moving surfaces are fully separated by a fluid (or gas). The friction force is determined by the viscosity of the fluid: The inner friction of the fluid is significant - Newtonian fluid.

Stribeck diagram



μ – *friction coefficient*
v – *relative velocity*
η – *viscosity of lubricant*
q – *surface pressure*

Forming – high pressure, therefore mainly mixed friction exists.

Friction regimes

Thick film state: Hydrodynamic friction. The thickness of the lubricant film is **one order of magnitude larger** than the contact surfaces' roughness. From the aspect of forming, the loadability of the surfaces is not significant.

Thin film state: The film thickness decreases due to increased pressure, and decrease of viscosity (effect of temperature). The thickness of the lubricant film is **3-5 times larger** than the contact surfaces' roughness. The tool and the workpiece is in contact in certain points, which causes higher friction coefficient than in the previous case. Wear effect.

Mixed friction state. The workpiece/tool **contact area is significant**. The thickness of the lubricant film is a maximum 3 times larger than the contact surfaces' roughness. By appropriate choice of lubricant few molecule thick layer is formed on the surfaces, which prevent the metal-metal contact and so reduces the wear.

Boundary friction state. The load is transmitted through the contacting surfaces, but the boundary layer on the surfaces prevents direct contact.

The friction's effect on forming processes

The friction leads to **unequal distribution of strain**, and thus influences the stress state. Different strain leads to **different strain hardening**: therefore the mechanical properties will be inhomogeneous.

Due to the friction forces **higher forming forces** are needed, and the **load on dies is higher** as well.

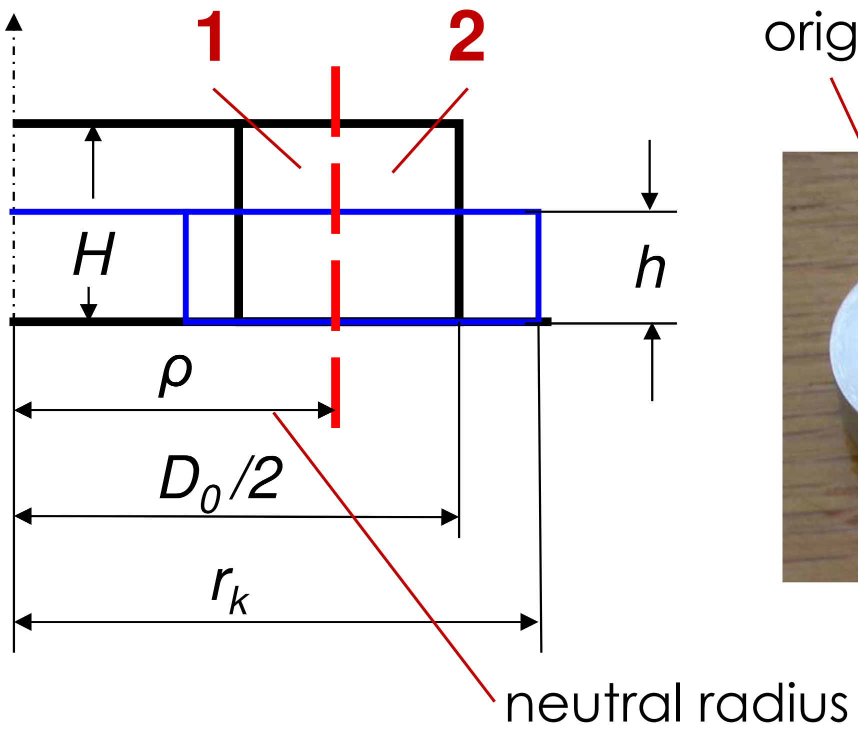
The **wear** caused by friction **decreases the service life of the die** and **reduces the surface quality of the workpieces**.

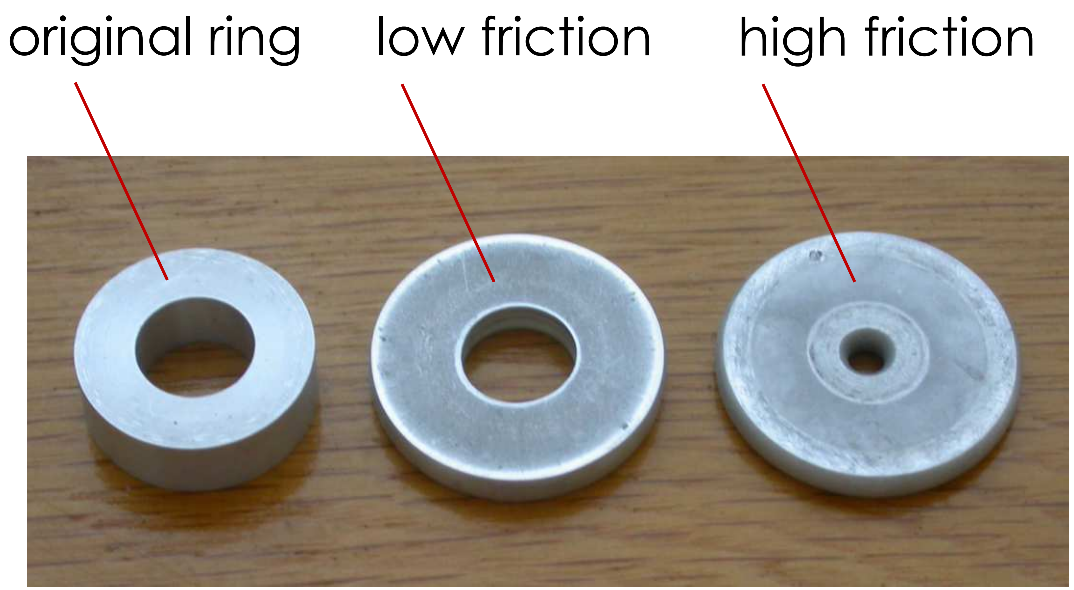
The **harmful consequences** of friction **can be reduced by lubrication**. This can make the technology more complicated.

The **treatment and lubrication** of the surfaces **prior to the forming** as well as the **removal of the lubrication after is costly**.

Friction coefficient measurement

Ring upsetting



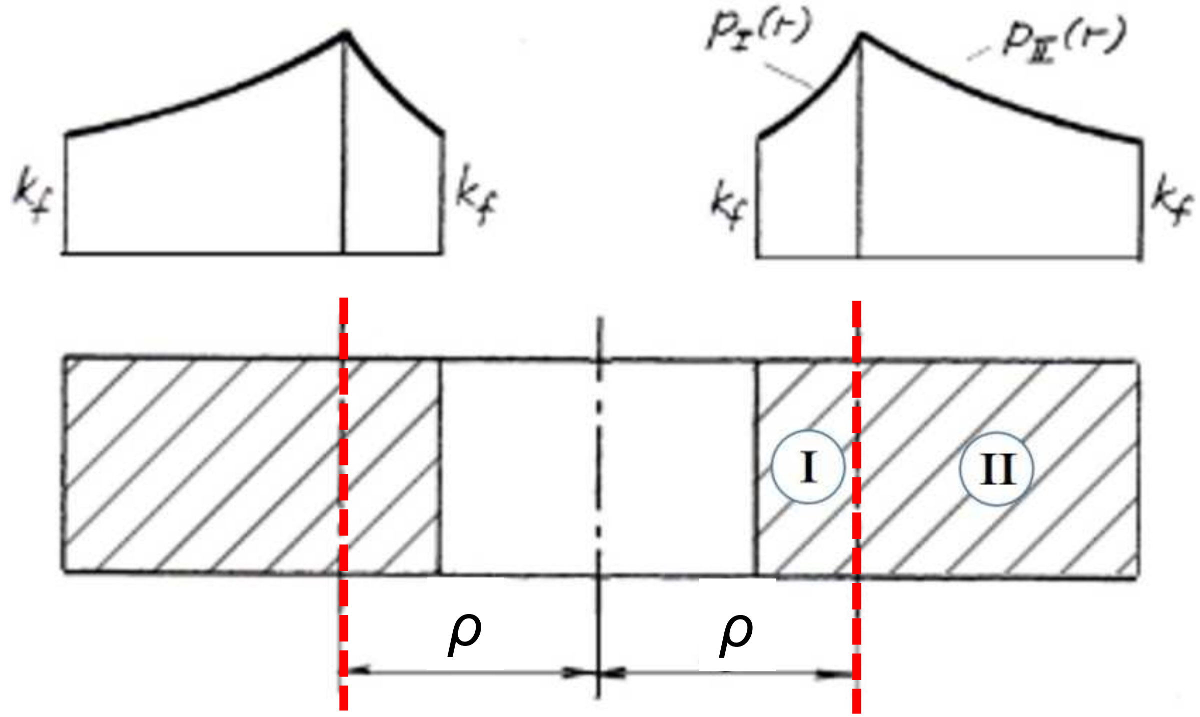


Volume 1 flows in, volume 2 flows out, no radial flow through the red line.

At the red line the axial stresses for the two volumes are equal.
From this equilibrium, the friction coefficient can be calculated.
These calculations are complicated → using nomograms.

Friction coefficient measurement

Ring upsetting



At the red line, not only the axial pressure (p) for the two volumes is equal, but the radial stresses are also equal with opposite signs. Starting with the latter equilibrium the friction coefficient can be calculated:

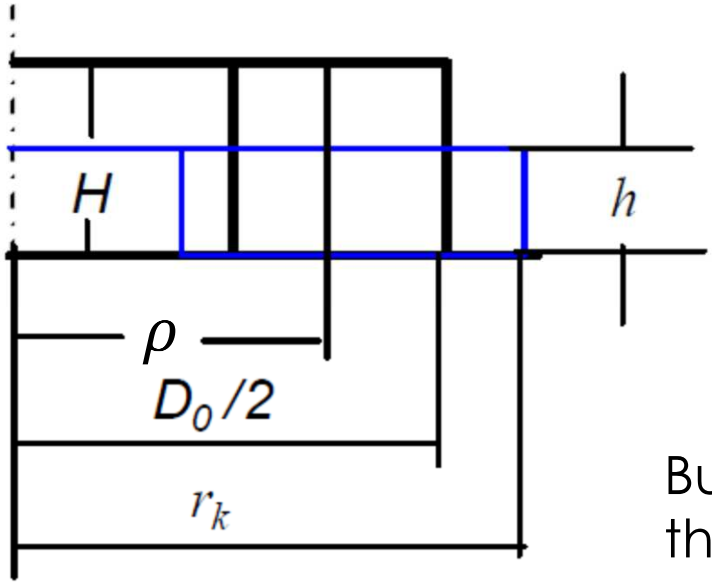
$$\sigma_{rk} = \sigma_{rb}$$

Friction coefficient measurement

After a long theoretical solution and simplifications (see at the end of the presentation):

$$\ln \frac{r_k^2\left(\rho^2+\sqrt{3r_b^4+\rho^4}\right)}{r_b^2\left(\rho^2+\sqrt{3r_k^4+\rho^4}\right)}=\frac{2m}{h}\left(r_k+r_b-2\rho\right)$$

Calculation of ρ from the volume constancy for the outer region:

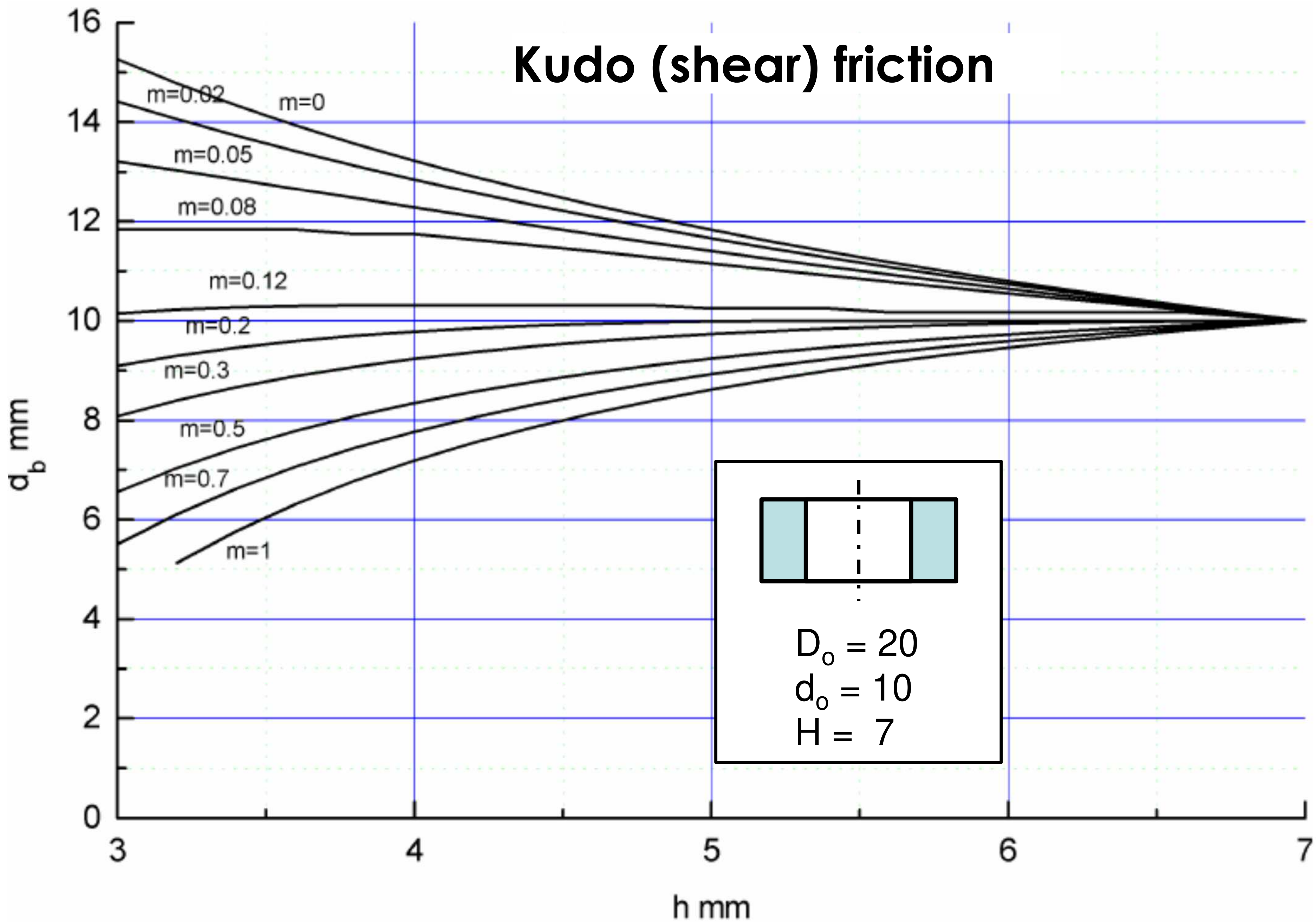


$$\left(D_0^2-4\rho^2\right)\frac{\pi}{4}H=\left(r_k^2-\rho^2\right)\pi h$$

$$\rho=\sqrt{\frac{D^2H-4r_k^2h}{4(H-h)}}$$

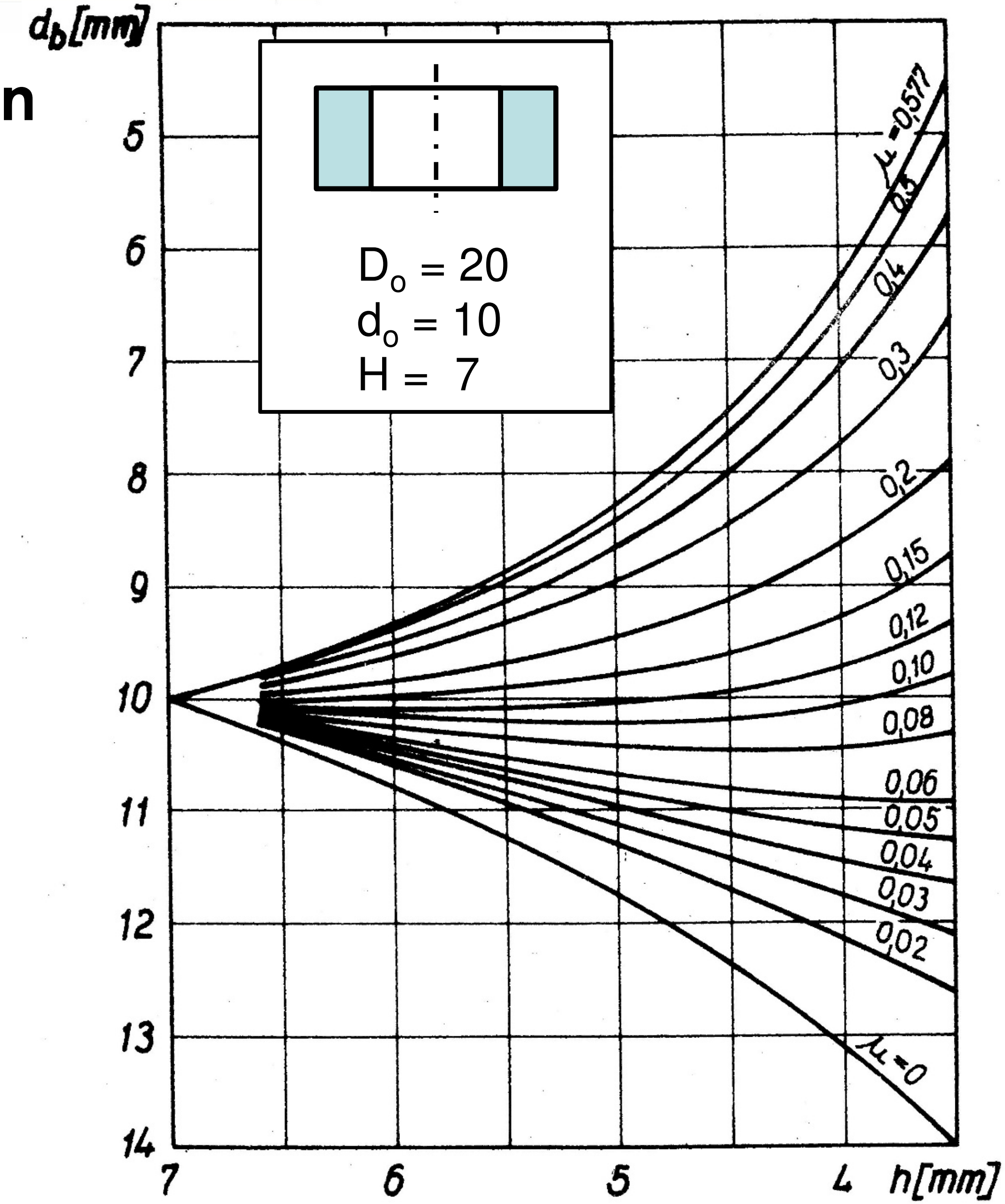
But these calculations are complicated, therefore $\rightarrow$ use nomograms.

Friction coefficient measurement



Friction coefficient measurement

Coulomb friction



Friction coefficient measurement

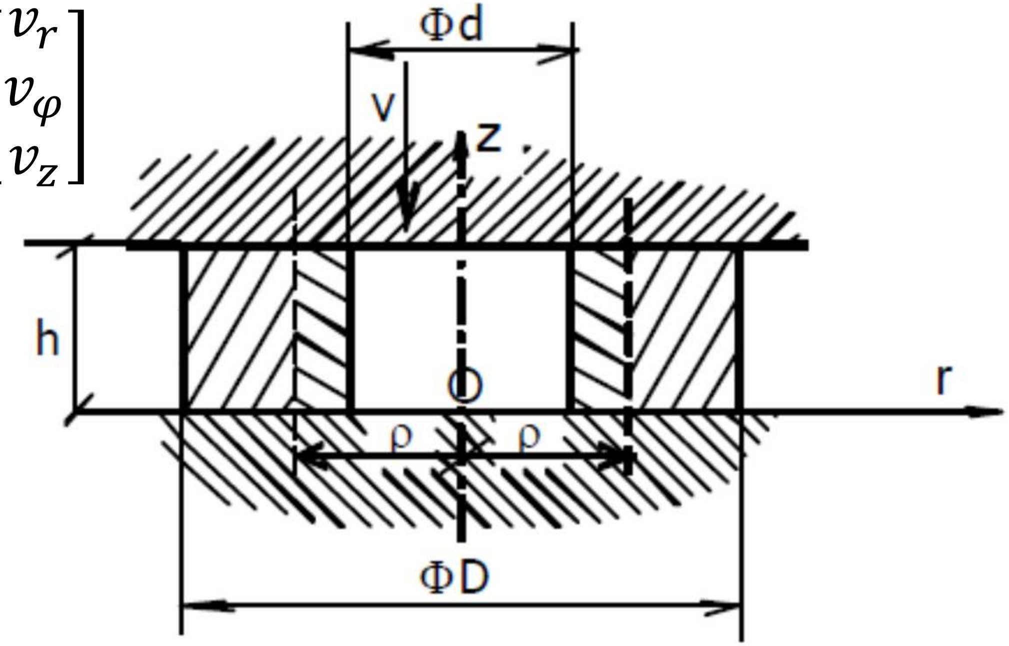
Ring upsetting solution

Kinematic analysis

$$z = 0 \quad v_z = 0$$
$$z = h \quad v_z = -v_0$$

$$v_z = -\frac{v_0}{h}$$

$$v = \begin{bmatrix} v_r \\ v_\varphi \\ v_z \end{bmatrix}$$



Incompressibility

$$div\ v = \frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0$$

$$\frac{1}{r}\frac{\partial}{\partial r}(v_r r) + \frac{\partial v_z}{\partial z} = 0$$

$$v_r r = \int -r\frac{\partial v_z}{\partial z} dr$$

$$v_r = \frac{v_0 r}{2h} + C$$

Strain rates

$$\xi_{rr} = \frac{\partial v_r}{\partial r} \qquad \xi_{\varphi\varphi} = \frac{v_r}{r} \qquad \xi_{zz} = \frac{\partial v_z}{\partial z}$$

At $r = \rho$ the radial velocity is zero, so C can be calculated (next slide)

Friction coefficient measurement

Calculation of C

$$v_{r\ at\ r=\rho} = 0 = \frac{v_0 \rho}{2h} + C$$

$$C = -\frac{v_0}{2h}\rho^2$$

$$v_r = \frac{v_0}{2h}\left(r - \frac{\rho^2}{r}\right)$$

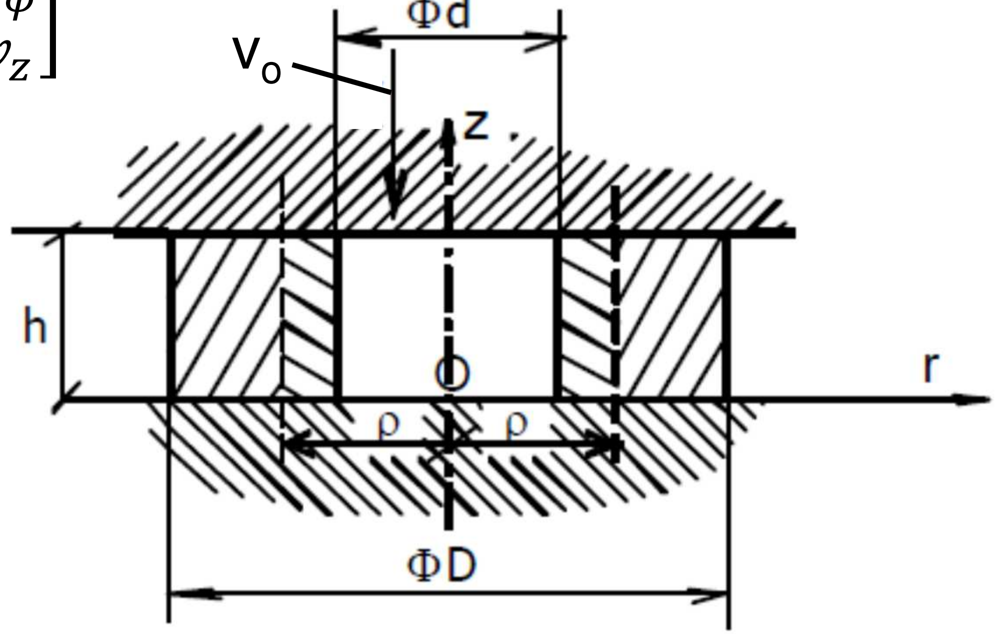
By using this, the strain rates

$$\xi_{rr} = \frac{v_0}{2h}\left(1 + \frac{\rho^2}{r^2}\right)$$

$$\xi_{\varphi\varphi} = \frac{v_0}{2h}\left(1 - \frac{\rho^2}{r^2}\right)$$

$$\xi_{zz} = -\frac{v_0}{h}$$

$$v = \begin{bmatrix} v_r \\ v_\varphi \\ v_z \end{bmatrix}$$



Equivalent strain rate

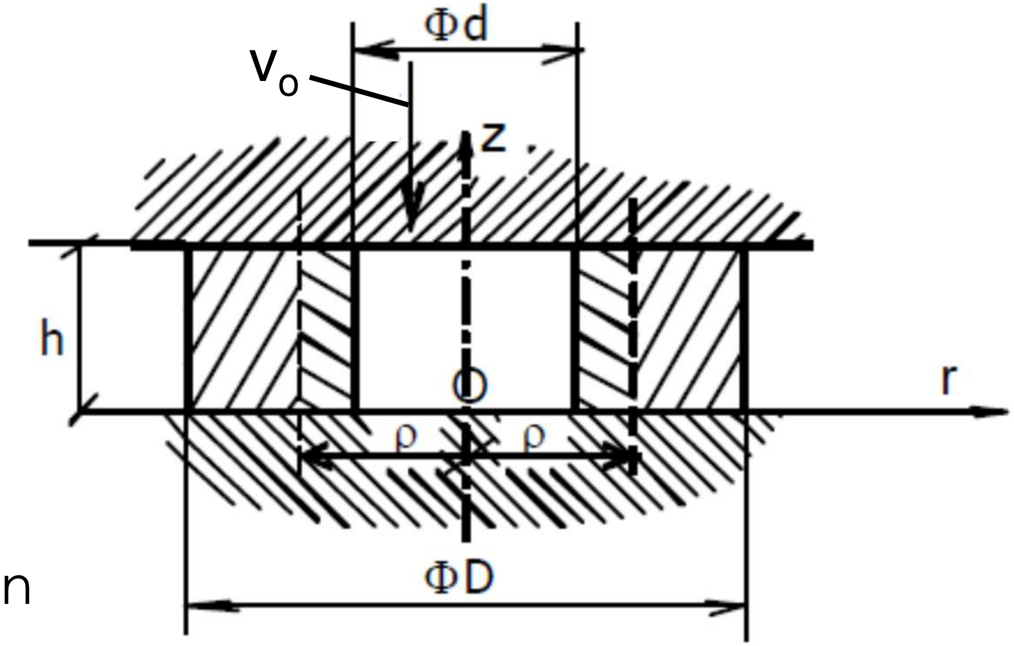
$$\bar{\xi} = \frac{v_0}{\sqrt{3}h}\sqrt{3 + \frac{\rho^4}{r^4}\left(1 + \frac{\rho^2}{r^2}\right)}$$

Friction coefficient measurement

Equilibrium

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{\sigma_{rr} - \sigma_{\varphi\varphi}}{r} + \frac{\partial \sigma_{rz}}{\partial z} = 0,$$

$$\frac{\partial \sigma_{zr}}{\partial r} + \frac{\sigma_{zr}}{r} + \frac{\partial \sigma_{zz}}{\partial z} = 0$$



According to the Levy-Mises equation

$\boldsymbol{\xi} = \dot{\lambda}\boldsymbol{\sigma}'$ Here $\boldsymbol{\sigma}'$ is the deviator stress

$$\frac{\sigma_{\varphi\varphi} - \sigma_{zz}}{\sigma_{rr} - \sigma_{\varphi\varphi}} = \frac{\dot{\varepsilon}_{\varphi\varphi} - \dot{\varepsilon}_{zz}}{\dot{\varepsilon}_{rr} - \dot{\varepsilon}_{\varphi\varphi}} = \frac{3r^2 - \rho^2}{2\rho^2}, \quad \frac{\sigma_{zz} - \sigma_{rr}}{\sigma_{rr} - \sigma_{\varphi\varphi}} = \frac{\dot{\varepsilon}_{zz} - \dot{\varepsilon}_{rr}}{\dot{\varepsilon}_{rr} - \dot{\varepsilon}_{\varphi\varphi}} = -\frac{3r^2 + \rho^2}{2\rho^2}$$

Friction coefficient measurement

Yield criteria

$$\sigma_{Mises} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{rr}-\sigma_{\varphi\varphi})^2+(\sigma_{zz}-\sigma_{\varphi\varphi})^2+(\sigma_{rr}-\sigma_{\varphi\varphi})^2+6(\sigma_{r\varphi}^2+\sigma_{rz}^2+\sigma_{z\varphi}^2)} = \sigma_{flow}$$

The $z = 0$ plane is at the half height of the ring: $\sigma_{rz} = \sigma_{zr} = \mp\frac{2\tau}{h}z$

$$\left(\sigma_{rr}-\sigma_{\varphi\varphi}\right) = \frac{2}{\sqrt{3}}\frac{\rho^2}{\sqrt{3r^4+\rho^4}}\sqrt{\sigma_f^2-\frac{12\tau^2}{h^2}z^2}$$

Equilibrium equation containing the yield criteria:

$$\frac{\partial\sigma_{rr}}{\partial r}+\frac{1}{r}\frac{2}{\sqrt{3}}\frac{\rho^2}{\sqrt{3r^4+\rho^4}}\sqrt{\sigma_f^2-\frac{12\tau^2}{h^2}z^2}\mp\frac{2\tau}{h}=0$$

Apply the shear friction model: $\tau = m\,\tau_{max} = m\,\tau_{flow} = m\frac{\sigma_{flow}}{\sqrt{3}}$

$$sign(\tau) = -sign(v_{rel})$$

Friction coefficient measurement

Calculate the radial stress in the z = 0 plane

$$\frac{d\sigma_r}{dr}+\frac{1}{r}\frac{2}{\sqrt{3}}\frac{\rho^2}{\sqrt{3r^4+\rho^4}}\sigma_f-\frac{2m\sigma_f}{h\sqrt{3}}=0$$

In the external zone (k):

$$\sigma_{rrk}=-\frac{2}{\sqrt{3}}\sigma_f\int_r^{r_k}\frac{\rho^2}{r\sqrt{3r^4+\rho^4}}dr+\frac{2}{\sqrt{3}}m\frac{\sigma_f}{h}\int_r^{t_k}dr$$

$$\sigma_{rrk}=\frac{\sigma_f}{\sqrt{3}}\ln\frac{r^2\left(\rho^2+\sqrt{3r_k^4+\rho^4}\right)}{r_k^2\left(\rho^2+\sqrt{3r^4+\rho^4}\right)}+\frac{2\sigma_f}{\sqrt{3}h}m(r_k-r)$$

In the internal zone (b):

$$\sigma_{rrb}=-\frac{2}{\sqrt{3}}\sigma_f\int_{r_b}^{r}\frac{\rho^2}{r\sqrt{3r^4+\rho^4}}dr-\frac{2}{\sqrt{3}}m\frac{\sigma_f}{h}\int_{r_b}^{r}dr$$

$$\sigma_{rrb}=\frac{\sigma_f}{\sqrt{3}}\ln\frac{r_b^2\left(\rho^2+\sqrt{3r^4+\rho^4}\right)}{r^2\left(\rho^2+\sqrt{3r_b^4+\rho^4}\right)}-\frac{2\sigma_f}{\sqrt{3}h}m(r-r_b)$$

Friction coefficient measurement

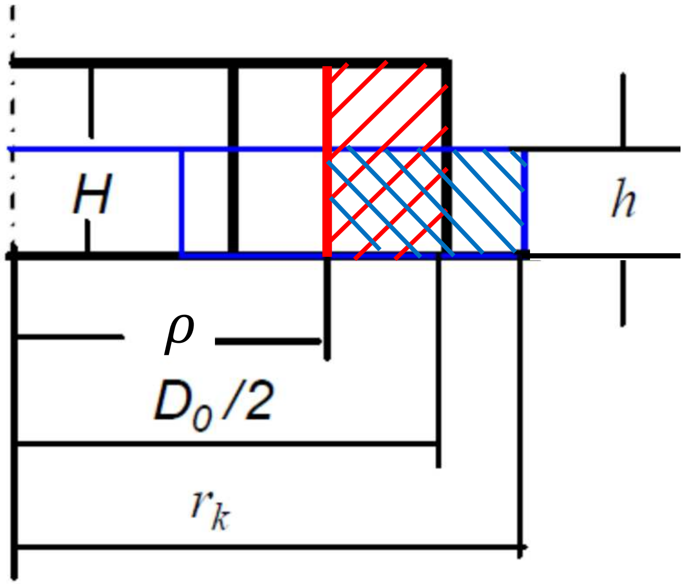
At the $r = \rho$ radius, which separates the two regions, the radial stresses are equal with opposite sign

$$\sigma_{rrk} = \sigma_{rrb}$$

After simplification

$$\ln \frac{r_k^2\left(\rho^2 + \sqrt{3r_b^4 + \rho^4}\right)}{r_b^2\left(\rho^2 + \sqrt{3r_k^4 + \rho^4}\right)} = \frac{2m}{h}\left(r_k + r_b - 2\rho\right)$$

Calculation of ρ from the volume constancy for the outer region



$$\left(D_0^2 - 4\rho^2\right)\frac{\pi}{4}H = \left(r_k^2 - \rho^2\right)\pi h$$

$$\rho = \sqrt{\frac{D^2 H - 4r_k^2 h}{4(H-h)}}$$