MATHEMATICAL AND PHYSICAL MODELING OF THE FLAT ROLLING PROCESS

by

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OUTLINE

- INTRODUCTION
- THEORY OF PLASTICITY
- ROLLING MILL
- ROLLING FORCES
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- TEMPERATURE EFFECTS ON ROLLING
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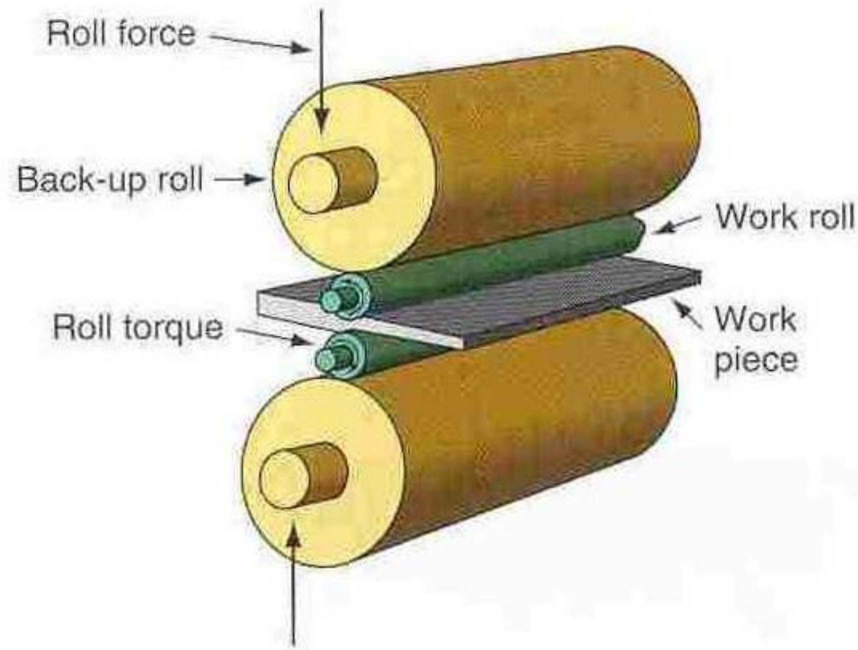
- OTHER TYPES OF ROLLING – TEMPER, ACUMULATIVE, FLEXIBLE
- RESULTS AND FUTURE COMPARISON
- COMPUTATIONAL SIMULATION
- CONCLUSIONS

INTRODUCTION

- THE FLAT ROLLING PROCESS
  - Reduce thickness to a pre-determined final thickness
  - Hot, Warm and Cold rolling
  - Work and Back-up rolls
  - Finishing and Roughening mills
  - Roll separating forces and roll torques



INTRODUCTION

- THE HOT ROLLING PROCESS
  - Reheating Furnaces
    - Heated up to 1200 – 1250 C for steel, 500 – 550 C for aluminum
    - Removing cast dendrite structures
    - Dissolving most of alloying elements
    - Decreases hard precipitates
  - Roughing mill
  - Coil box
  - Finishing mill

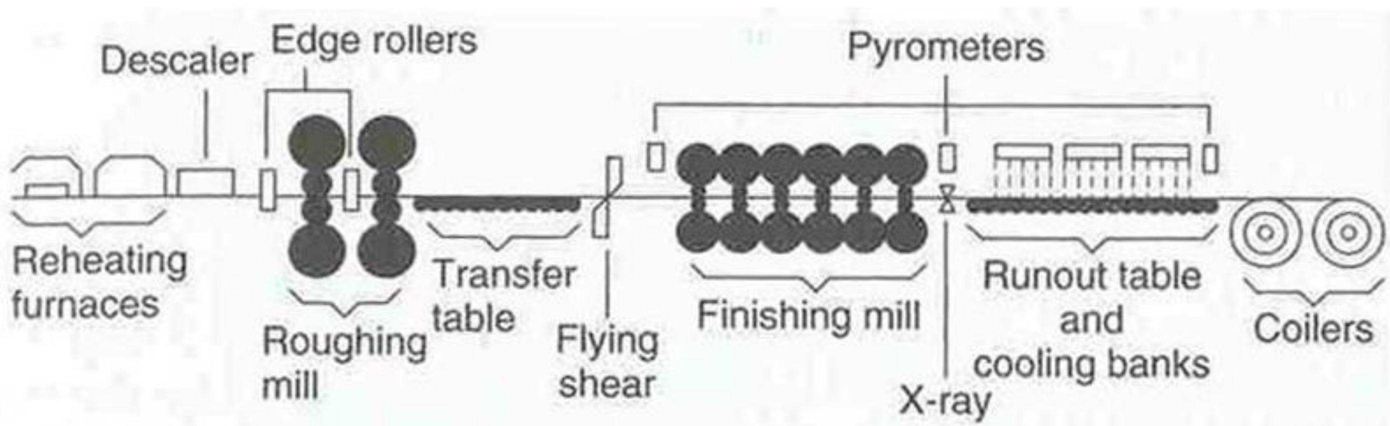


Figure is from John G. Lenard, (2007)

INTRODUCTION

- PHYSICAL QUANTITIES OF ROLLING

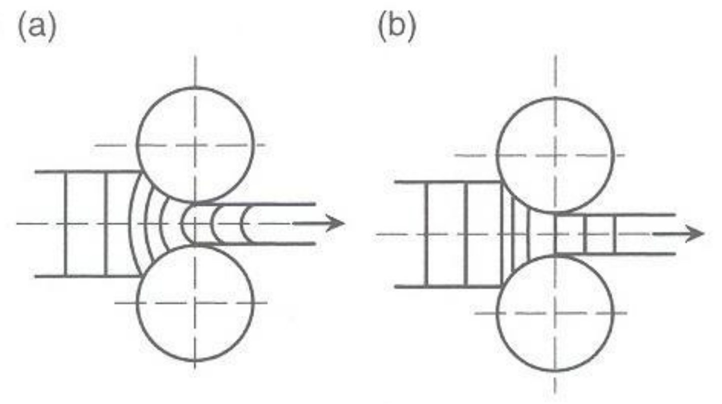
  - Roll separating force (P_r) in N/mm.
  - Roll pressure p in Pa.
  - Coefficient of friction μ
  - Width of the metal to be rolled w in mm.
  - Radius of the work roll R and deformed radius of the work roll R' in mm.
  - Contact length L in mm.
  - Entry thickness h_{entry}, exit thickness h_{exit} and the difference Δh in mm.
  - Shear stress τ in Pa.
  - The angle between the vertical lines is ϕ
  - The torque per width M in N.
  - r is the reduction in %.

THEORY OF PLASTICITY

- MATERIAL CHARACTERISTICS OF STEEL
  - A metallic alloy with variable carbon content
  - Relatively high resistance to deformation
  - High strength and ductility and good behavior at high temperatures
  - Ductility as much as 40 %
  - Strength as much as 1250 MPa
  - Transformation-induces plasticity (TRIP)
  - Martensitic and magnese-boron steels
  - Advance high strength steels (AHSS)
  - Annealing after cold rolling
  - Entry temperature and strain rate have crucial effect
  - More than 50% reduction can be achieved

THEORY OF PLASTICITY

- HOMOGENEOUS AND NON-HOMOGENEOUS COMPRESSION
  - Experimentally studies
  - In homogeneous compression planes remain as planes
  - Easier to model the homogeneous compression
  - Schey determination – when average thickness $h_{ave} = \frac{(h_{entry} - h_{exit})}{2}$ divided by the length (L) is bigger than a unity, non-homogeneous.



THEORY OF PLASTICITY

- IDEAL PLASTIC DEFORMATION CRITERIA
  - Planes strain plastic flow
  - Width should also be considered as unchanged
  - All the energy is absorbed by the material and turned into plastic deformation
  - No energy lost in the elasticity
  - Also no elastic recovery is considered
  - Becomes handy in 2D analysis

THEORY OF PLASTICITY

- LIMITATIONS OF FLAT ROLLING

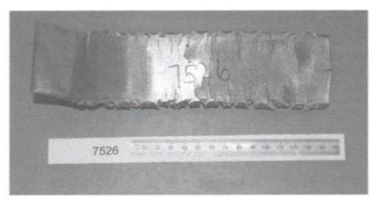
  - Minimum rollable thickness by Stone (1953)

$$h_{\min} = \frac{3.58 D \mu \sigma_{fm}}{E}$$

where D is the roll diameter in mm E is the elastic modulus in Pa, σ_{fm} is the average flow strength in Pa and μ is the coefficient of friction.

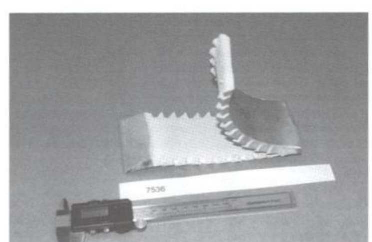
Claimed that in reality this does not exits.

  - Edge cracking



Edge cracking of an aluminum alloy, hot rolled at 505°C to a strain of 0.6 (Duly et al., 1998).

  - Alligatoring



Alligatoring and edge-cracking of an aluminum alloy, hot rolled at 497°C to a strain of 0.56.

Figures are from John G. Lenard, (2007)

ROLLING MILL

- HITCHCOOK'S RADIUS
  - Elasticity of the roll is considered
  - Hitchcock's equation (1935): $$R' = R\left[1+\frac{16\left(1-v^2\right)}{\pi E \Delta h}P_r\right]$$

  where R' is the flattened but still circular roll radius in mm, R is the original roll radius in mm, v is the Poisson's ratio, E is the Young's modulus of the roll in Pa, Δh is the thickness difference in mm and P_r is the roll separating force in N/mm.

  - In experiments the squeezed roll is more flattened than circular

ROLLING MILL

- ROLL BENDING
  - Deflection of the roll across its central axis
  - Maximum deflection occurs at the center
  - Rowe calculated the maximum deflection in mm (1977) as; $\Delta = \frac{PL^3}{EI} + 0.2\frac{PL}{AG}$

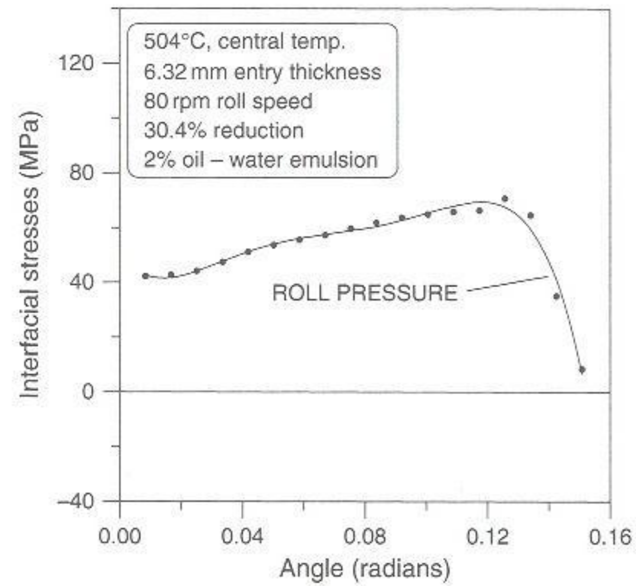
  P is the roll force in N, L is the length of the roll in mm, E is the elastic modulus in Pa, I is the moment of inertia, G is the shear modulus in Pa and A is the cross sectional area in mm^2

  - Rowe (1977) calculated the maximum deflection as; $\Delta = \frac{P\bar{L}^2(5L+24c)}{6\pi ED^4} + \frac{P\bar{L}}{2\pi GD^2}$

  $\bar{L}$ is the half of the bearing length in mm, D is the diameter of the roll in mm and c is the length of the roll in mm,

ROLLING FORCES

- ROLL PRESSURE AND ROLL SEPERATING FORCE
  - Roll pressure is the main physical source of the process
  - Roll separating force is the main goal in calculations in N/mm
  - They are related in all mathematical models
  - Roll pressure varies over the surface
  - Proportional
  - Increased with reduction
  - Roll separating force is used in calculating other quantities
  - Friction, entry thickness and strain hardening coefficient increase both of them
  - Cold rolling requires more than hot rolling
  - Needs to be determined before installation

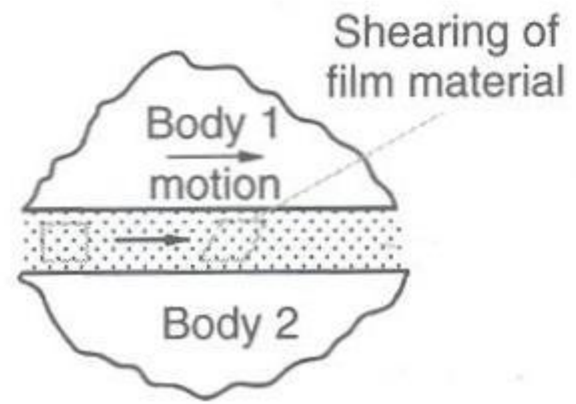


The roll pressure distribution.

Figure is from John G. Lenard, (2007)

ROLLING FORCES

- SHEAR STRESSES
  - Created due to the roll pressure
  - As a result of relative motion between roll and the strip
  - Acting tangential to the surface
  - Depends on coefficient of friction and roll pressure
  - Calculated as: $\tau = \mu p$
  - Direction is always opposite to the relative motion
  - Its sign changes in calculations due to previous reason
  - At neutral point it vanishes



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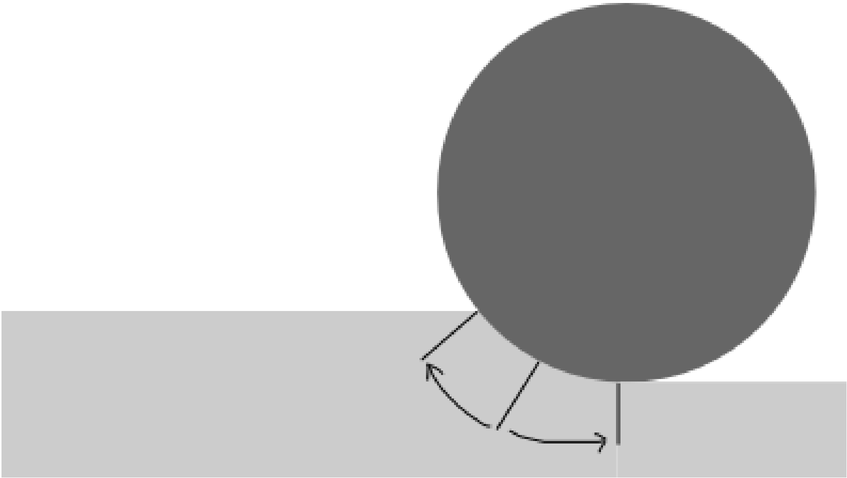
ROLLING FORCES

- NEUTRAL POINT
  - Backward region, strip is slower
  - neutral point, same speed as roll's surface
  - forward region, strip is faster
  - Conservation of mass
  - No relative motion occurs at this point
  - $\tau = 0$
  - Not in the middle
  - Needs to be determined in some calculations
  - Neutral or no-slip region

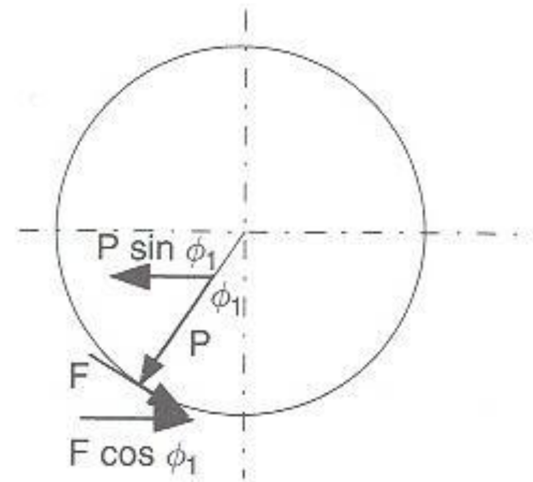


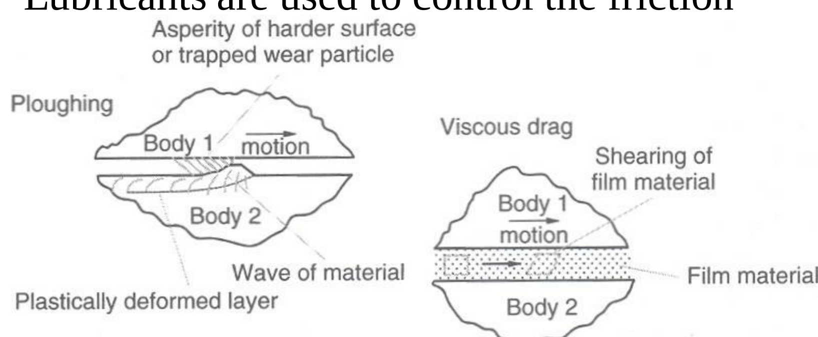
TRIBOLOGY

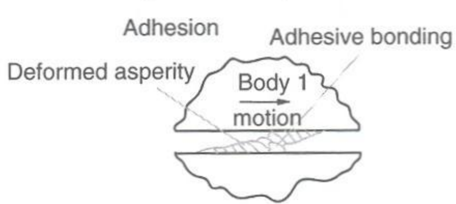
- COEFFICIENT OF FRICTION
  - Reason for the process to start and to move forward

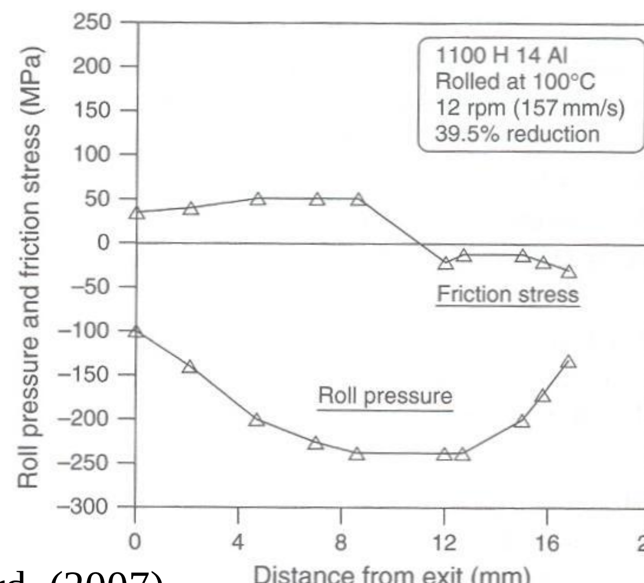
$$\mu_{\min} = \tan \phi_{bite}$$

  - Increases the required forces to drive
  - It varies over the surface
  - Oxidation on hot rolling changes it
  - Adhesion and apparent contact area
  - Lubricants are used to control the friction









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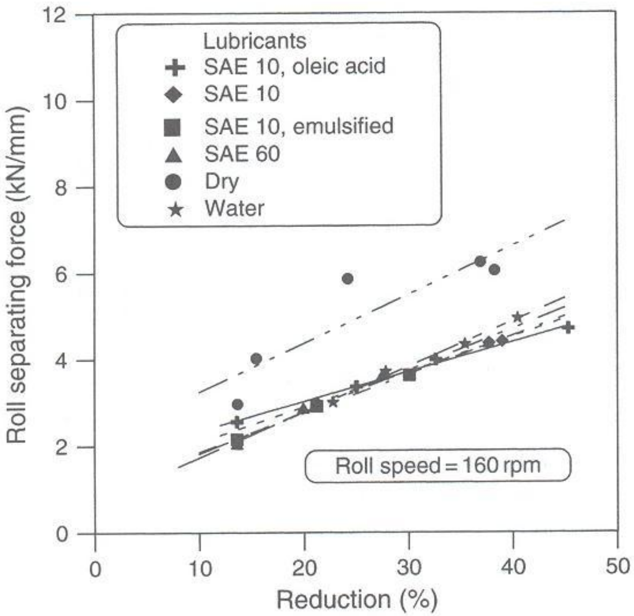
TRIBOLOGY

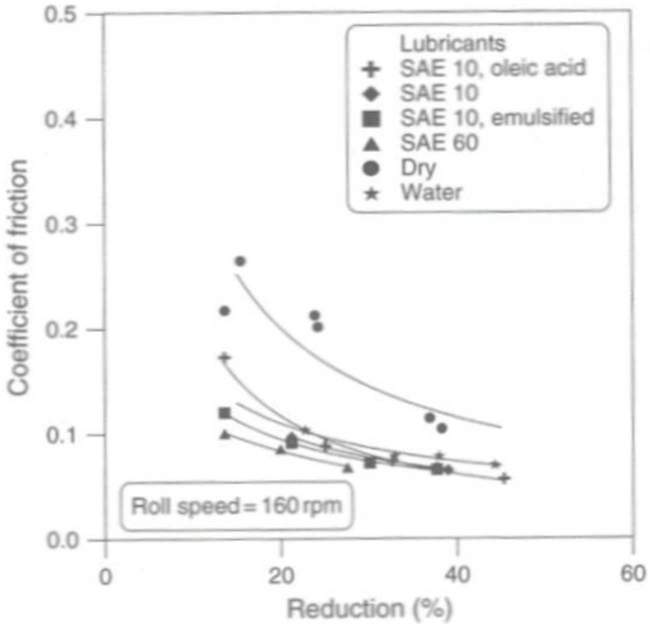
- LUBRICANT
  - Oil- water emulsions are the most common lubricant
  - The viscosity: $\tau = \eta\dot{\gamma}$ $\mu = \dfrac{\eta}{\rho}$

    η is the dynamic viscosity in Pa.s, μ is the kinematic viscosity in m^2/s, $\dot{\gamma}$ is the shear strain rate, ρ is the density.

  - Viscosity – Pressure: $\eta = \eta_0 \exp(\gamma p)$ $\eta = \eta_0 (1 + Cp)^n$

    η_0 is the viscosity under atmospheric pressure and γ is the pressure-viscosity coefficient and p is the pressure. C and n are constants.





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TRIBOLOGY

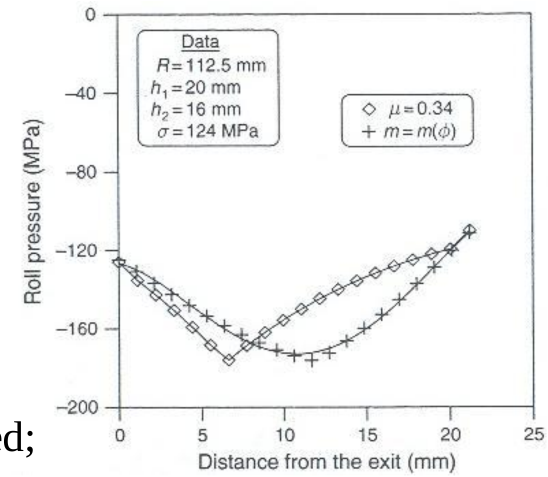
- FRICTION FACTOR

$$\tau = mk \qquad 0 \le m \le 1$$

  - 1-D equation could be written as;

$$\frac{dp}{dx} = \frac{2k}{h_{exit}R + x^2}(2x - mR)$$

  - The friction factor could be determined in terms of load and speed;



$$m = \bar{a}\left(x^2 - x_{np}{}^2\right)p + \bar{b}\tan^{-1}\left(\frac{\Delta v}{q}\right)$$

Figure is from John G. Lenard, (2007)

  - The relative velocity is given;

$$\Delta v = v_r \frac{x_{np}{}^2 - x^2}{h_{exit}R + x^2}$$

$\bar{a}, \bar{b}$ are constants to be determined, q is a constant taken as 0.1

MATHEMATICAL MODELING OF ROLLING

- SCHEY'S MODEL
  - Schey's model, roll separating force per unit with;

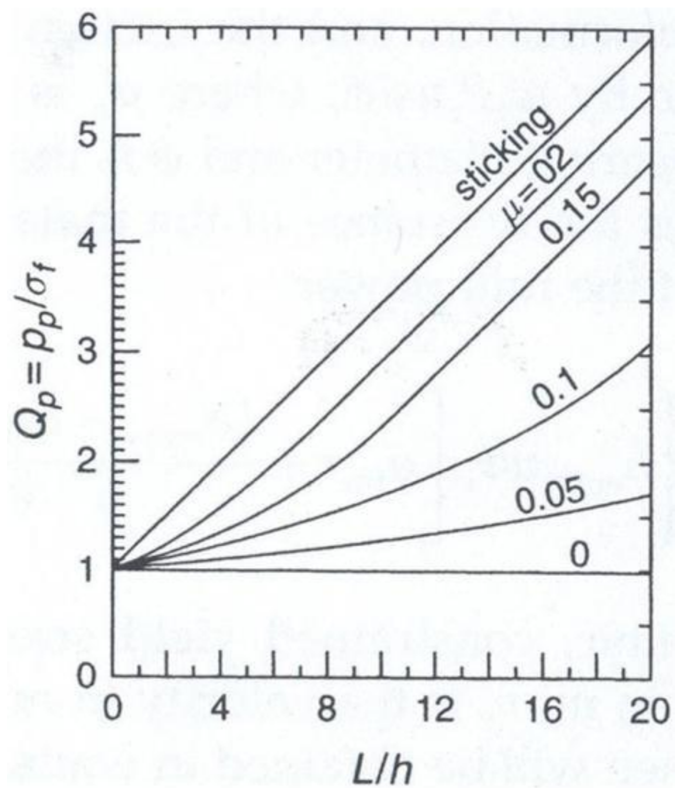
$$P_r = 1.15 Q_p \sigma_{fm} L$$

  - Average flow strength; σ_{fm} (in Pa) is obtained by;

$$\sigma_{fm} = \frac{1}{\varepsilon_{\max}} \int_0^{\varepsilon_{\max}} \sigma(\varepsilon) d\varepsilon$$

Q_p is the pressure intensification factor which is roll pressure divided by average flow strength p/σ_{fm}, $\varepsilon_{\max}$ is the maximum strain and L is the contact length of rolling in m.

  - Q_p can be obtained by the graph defined by Schey



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MATHEMATICAL MODELING OF ROLLING

- SIM'S MODEL
  - Roll separating force in N/mm: $P_r = 2kLQ_p$

    Assumed that the angles in the roll gap are very small ($\sin\phi = \tan\phi = \phi$). Interfacial shear stress is negligible and there is a sticking friction between the roll and the strip ($\tau = k$).

  - Pressure intensification factor:

$$Q_p = \left[\frac{\pi}{2}\sqrt{\frac{1-r}{r}} \tan^{-1}\sqrt{\frac{r}{1-r}} - \frac{\pi}{4} - \sqrt{\frac{1-r}{r}\frac{R'}{h_{exit}}} \ln\frac{h_{np}}{h_{exit}} + \frac{1}{2}\sqrt{\frac{1-r}{r}\frac{R'}{h_{exit}}} \ln\frac{1}{1-r} \right]$$

h_{np} is the thickness at the neutral point. r is the reduction. Units inside each fraction should be consistent. Used in many calculations because of its simplicity.

MATHEMATICAL MODELING OF ROLLING

- OROWAN'S MODEL
  - 1 - Dimensional equilibrium based model;

$$\frac{d\left(\sigma_x h\right)}{dx} + p\frac{dh}{dx} \mp 2\mu p = 0$$

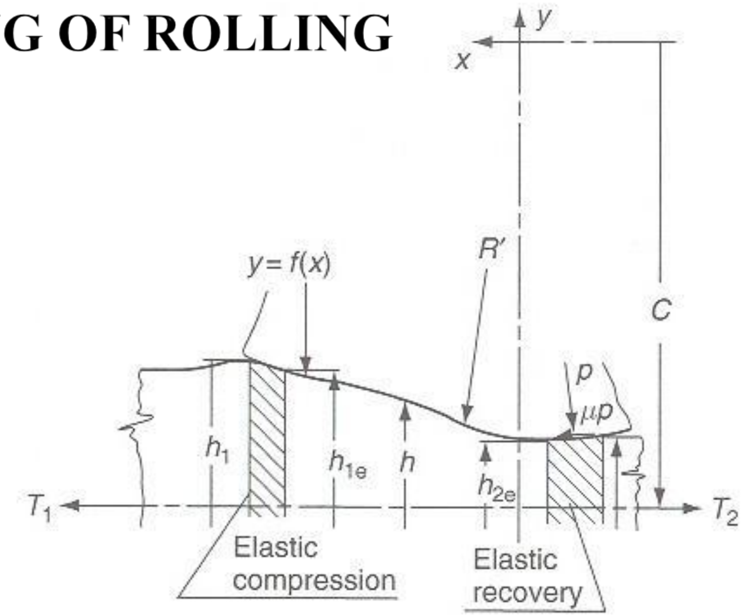
σ_x is the stress in the direction of rolling and $\mp$ is determined relative to the neutral point, p is the roll pressure.

  - Shear stress is given as $\tau = \mu p$ and using Huber – Mises criterion which is: $\sigma_x + p = 2k$
  - The formulation becomes:

$$\frac{dp}{dx} \pm 2\mu\frac{p}{h} = \frac{2k}{h}\frac{dh}{dx} + \frac{d(2k)}{dx}$$

k is the yield strength under pure shear.

MATHEMATICAL MODELING OF ROLLING



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- REFINEMENTS TO OROWAN MODEL
  - Published by Roychoudhury and Lenard (1984)

$$\frac{d}{dx}\left[h\left(p-2k\pm\tau\frac{dy}{dx}\right)\right]=2\left(p\frac{dy}{dx}\pm\tau\right)$$

$$y=f(x)=ax+b$$

  - Michell’s 2D elastic treatment (1990)

$$P_r=p\left[\int_{x_{entry}}^{x_n}\left(1+\mu\frac{dy}{dx}\right)dx+\int_{x_n}^{x_{exit}}\left(1+\mu\frac{dy}{dx}\right)dx+\int_{x_{entry}}^{x_n}\left(\mu-\frac{dy}{dx}\right)dx+\int_{x_n}^{x_{exit}}\left(\mu+\frac{dy}{dx}\right)dx\right]$$

$$\frac{M}{2}=p\int_{x_{entry}}^{x_n}\left[x-y\frac{dy}{dx}+\mu\left(y+xy\frac{dy}{dx}\right)\right]dx-p\int_{x_n}^{x_{exit}}\left[x-y\frac{dy}{dx}-\mu\left(y+x\frac{dy}{dx}\right)\right]dx$$

x_n, x_{entry} and x_{exit} are the positions on x axis at the entry, neutral and exit points.

TEMPERATURE EFFECTS ON ROLLING

- TEMPERATURE GAIN DUE TO PLASTIC DEFORMATION

  - The rise of temperature due to plastic deformation is:

$$\Delta T_{gain} = \frac{P_r L / R'}{\rho c_p h_{ave}}$$

P_r is in N/m, L and R' are in m, ρ is the density of the strip in kg/m^3 and c_p is the specific heat of strip in J/kgC.

  - Temperature rise by Roberts (1983) is: $$\Delta T_{gain} = \frac{\sigma_{fm}}{\rho c_p} \ln \frac{1}{1-r}$$

TEMPERATURE EFFECTS ON ROLLING

- TEMPERATURE LOSS DUE TO HEAT DISSIPATION TO THE AMBIENT AND THE ROLL

  - Temperature loss during hot rolling by Seredynski (1973) is:

$$\Delta T_{loss} = 60\alpha\sqrt{\frac{r}{h_{entry}R}}\left(T_{strip} - T_{roll}\right)\left[(1-r)\pi\rho c_p N\right]^{-1}$$

  α is the heat transfer coefficient of roll strip interface in $\mathrm{W/m^2K}$, N is the revolutions per minute. T_{strip} and T_{roll} are the strip and roll temperatures in Kelvin. ρ and c_p are of the roll.

  - Rise of roll's surface temperature estimated by Roberts (1983) is:

$$\frac{T_{roll} - T_0}{T_{strip} - T_0} = \alpha\sqrt{\frac{t}{kc_p\rho}}$$

  T_{roll} is the roll's surface temperature, T_0 is the roll's temperature below its surface. k is the thermal conductivity of the roll in W/mK. t is the contact time in seconds.

RECRYSTALLIZATION

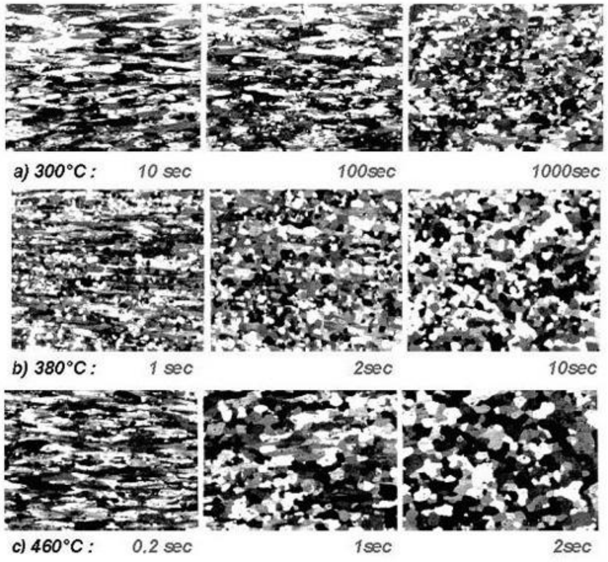
- STATIC RECRYSTALLIZATION
  - Recrystallization controlled rolling to achieve finer grains
  - Critical strain necessary for static recrystallization to occur
  - Larger the grain size, slower the rate of recrystallization
  - The temperature (in ºC) above recrystallization occurs is;

$$T_{NRX} = 887 + 464[C] + (6445[NB] - 644\sqrt{[Nb]}) + (732[V] - 230\sqrt{[V]}) + 890[Ti] + 363[Al] - 357[Si]$$

  - Avrami-Kolmogorov equation:

$$X = 1 - \exp\left[A \left(\frac{t}{t_X} \right)^k \right]$$

t is the hold time, X is the recrystallization volume fraction, t_X is the time for a given volume to crystallize, $A = \ln(X)$ and *k* is Avrami exponent.



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RECRYSTALLIZATION

- STATIC RECRYSTALLIZATION
  - Time for 50 % recrystallization is:

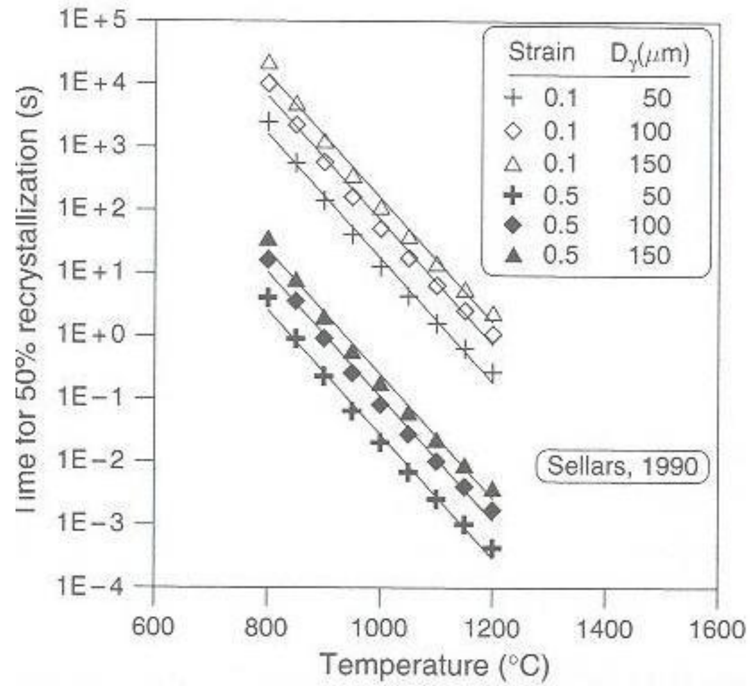
$$t_{0.5X} = B\varepsilon^{p} D_{\gamma}^{q} Z^{r} \dot{\varepsilon}^{s} \exp\left(\frac{Q_{RX}}{RT}\right)$$

ε is the strain, D_{γ} is the austenite grain size prior to deformation in µm, Z is the

Zener - Hollomon parameter defined as ;

$$Z = \dot{\varepsilon} \exp\left(Q/RT\right)$$

Q_{RX} is the activation energy for recrystallizaton in J/mole, R is the gas constant and T is the absolute temperature. B,p,q are given by Sellars (1990).



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RECRYSTALLIZATION

- STATIC RECRYSTALLIZATION
  - Recrystallized grain size:

$$D_r = C_1 + C_2 \varepsilon^m \dot{\varepsilon}^n D_\gamma^l \exp \frac{-Q_d}{RT}$$

C values, *m*, *n*, *l* are constants defined by Sellars. Q_d is the apparent activation energy.

  - Time for X % recrystallization in seconds is:

$$t = \left[\frac{\ln(1-X)}{A} \right]^{1/k} t_x$$

t_x is the time for a given volume to recrystallize.

RECRYSTALLIZATION

- DYNAMIC RECRYSTALLIZATION
  - Recrystallization during plastic deformation
  - Critical strain at which dynamic recrystallization starts, Zener-Hollomon parameter;

$$\varepsilon_c = AZ^p D_\gamma^q$$

A,*p*,*q* are material constants, D_γ is the austenite grain size.

  - Metadynamic recrystallization, starts during deformation and continues after deformation ends.

RECRYSTALLIZATION

- METADYNAMIC RECRYSTALLIZATION
  - Time for 50 % metadynamic recrystallization is:

$$t_{0.5} = A_1 Z^s \exp\left(\frac{Q}{RT}\right)$$

A_1 and s are the material constants defined by Hodgson. Q is the activation energy in J/mole.

  - The metadynamic grain size by Hodgson;

$$D_{MD} = AZ^u$$

  - Grain size during metadynamic recrystallization (in μm)is:

$$D(t) = D_{DRX} + (D_{MD} - D_{DRX})X_{MD}$$

X_{MD} is the volume fracture after metadynamic recrystallization. D_{DRX} is the grain size after dynamic recrystallization in μm.

ROLL TORQUE

- CALCULATION
  - Torque to drive the roll can be calculated in terms of roll separating force (P_r):

$$M = \frac{P_r L}{2}$$

  - The torque M is per unit width so the unit is N.
  - It is assumed that P_r acts at the middle of the contact and the contact length is linear
  - Linear length approximation may give bad results

ROLL POWER

- CALCULATION
  - The power to drive the mill in Watts:

$$P = P_r w L \frac{v_r}{R'}$$

v_r is the roll's surface speed in m/s. *w* is the width of the strip being rolled. R' is the flattened but still circular radius in mm.

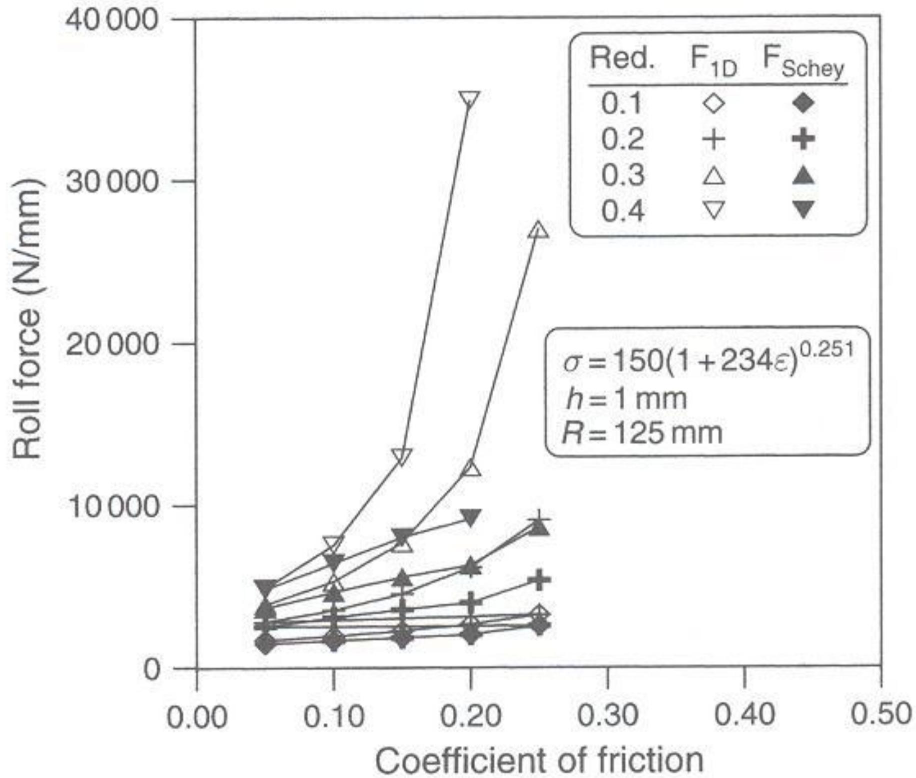
  - Overall power requirement by Rowe for four-high mill;

$$P_{total} = \frac{1}{\eta_m \eta_t}\left(2P + 4P_n\right)$$

η_m, η_t are the efficiencies of the driving motor and the transmission. P_n is the power loss on bearings due to friction in Watts.

INFLUENCE OF PHYSICAL QUANTITIES

- THE SENSITIVITY OF ROLL SEPERATING FORCE TO COEFFICIENT OF FRICTION AND REDUCTION
  - Predicted with using Schey's and refined 1D model



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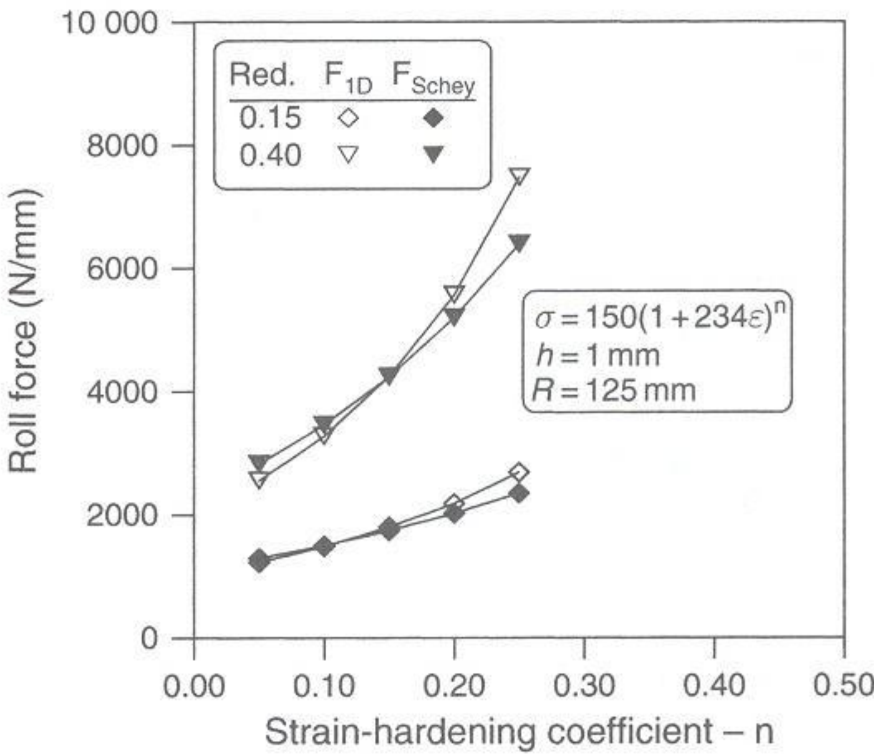
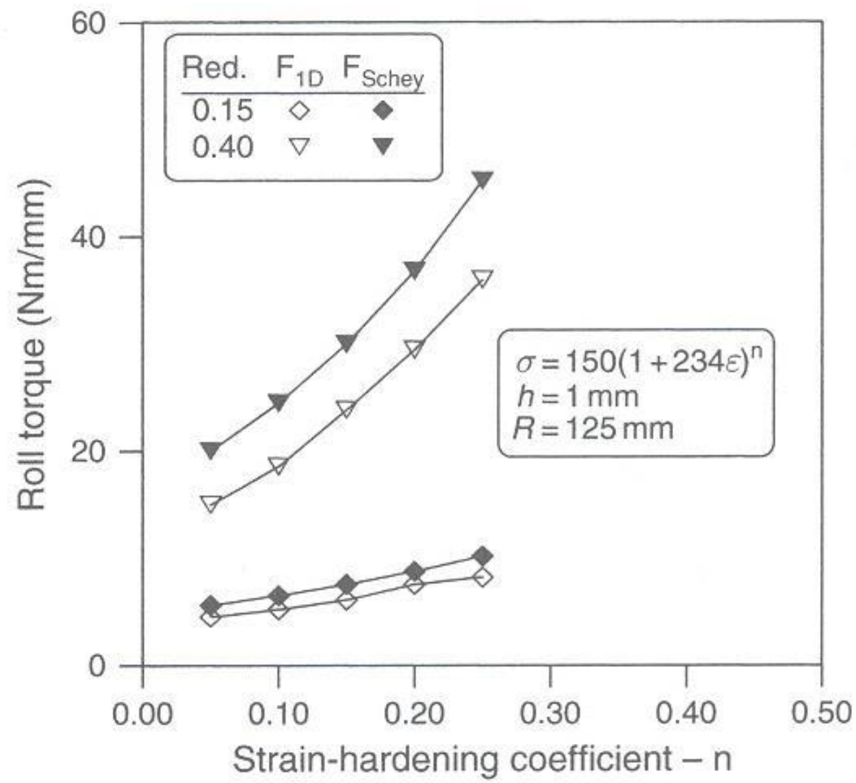
INFLUENCE OF PHYSICAL QUANTITIES

- THE SENSITIVITY OF ROLL SEPERATING FORCE AND ROLL TORQUE TO STRAIN HARDENING COEFFICIENT





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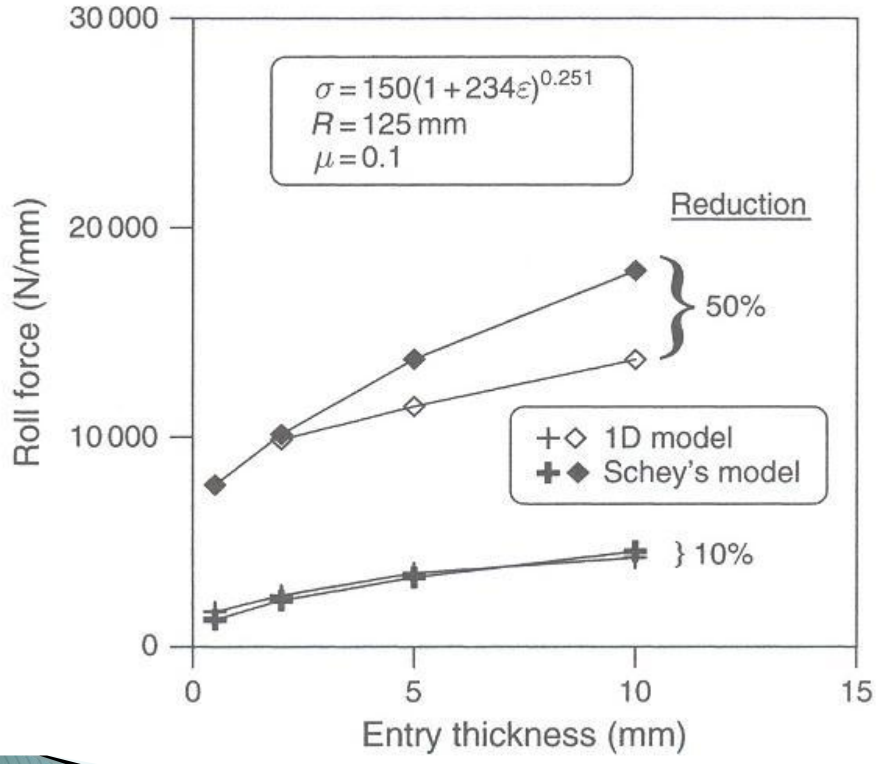
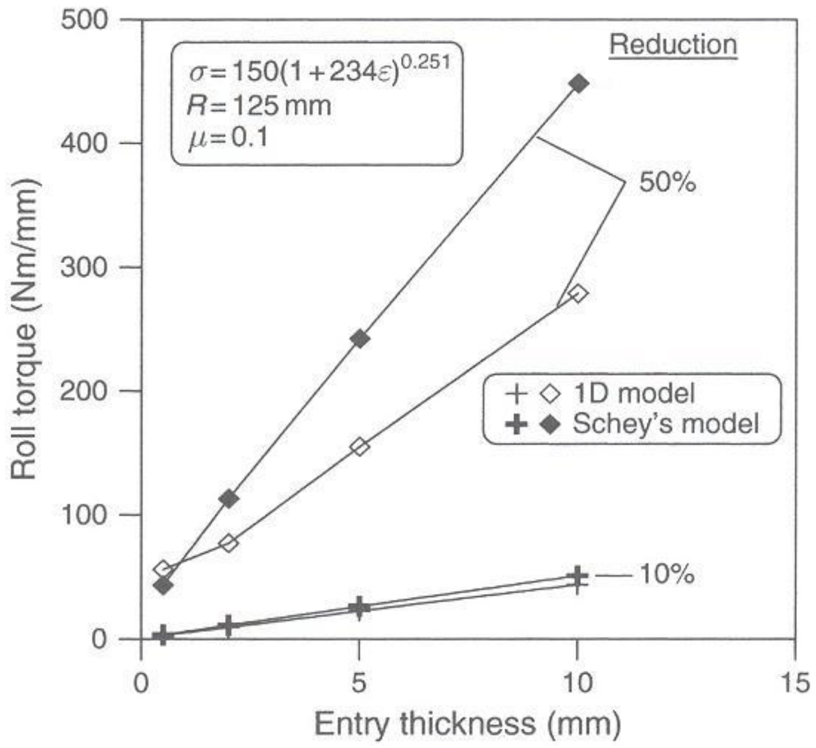
INFLUENCE OF PHYSICAL QUANTITIES

- DEPENDENCE OF ROLL SEPERATING FORCE AND ROLL TORQUE ON THE ENTRY THICKNESS





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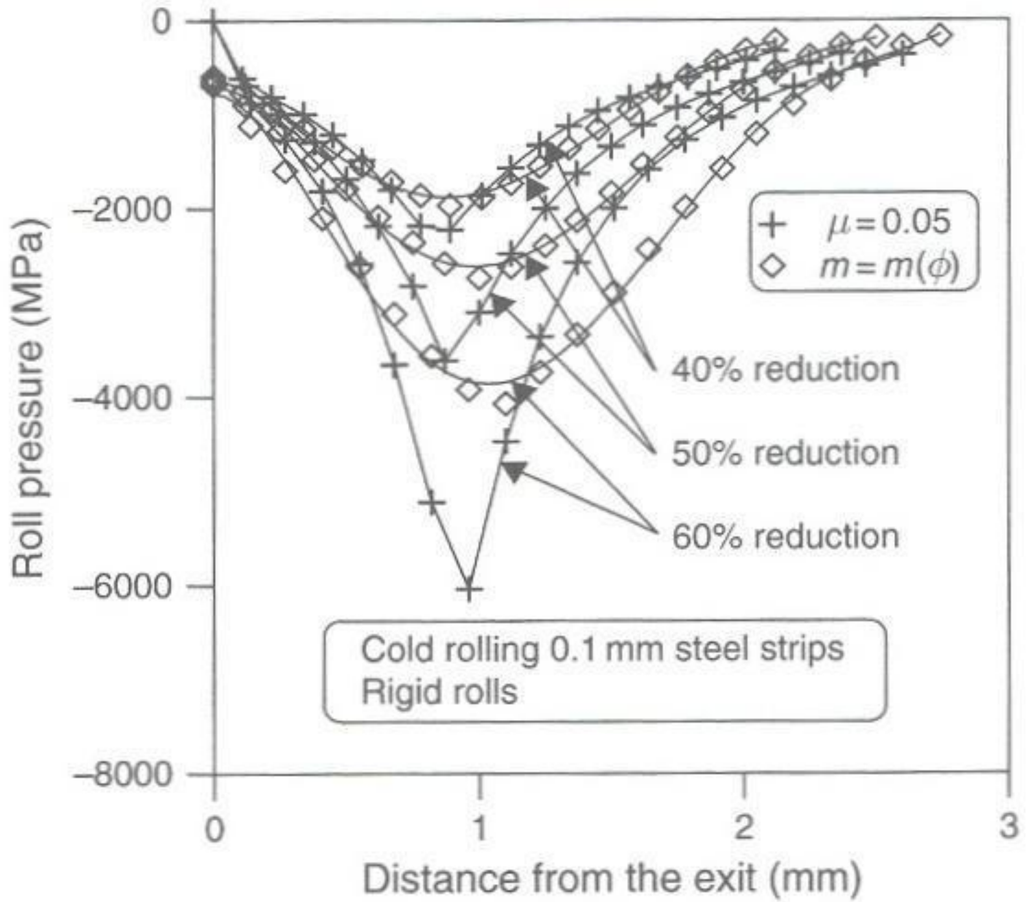
INFLUENCE OF PHYSICAL QUANTITIES

- ROLL PRESSURE DISTRIBUTION



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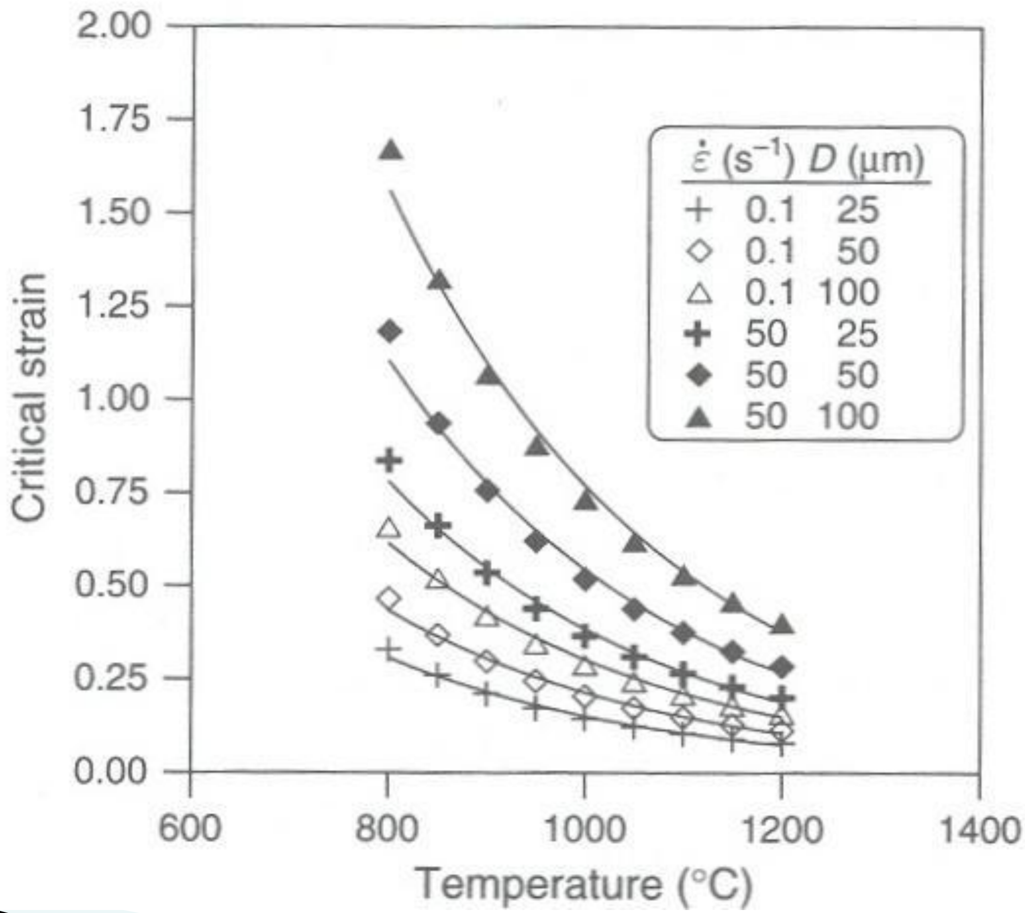
INFLUENCE OF PHYSICAL QUANTITIES

- THE CRITICAL STRAIN



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TEMPER ROLLING

- THE TEMPER ROLLING PROCESS

  - To suppress the yield point extension
  - Create Lüder’s lines.
  - Low reduction of thickness 0.5 – 5 %.
  - Production of required metallurgical properties, surface finish and flatness.
  - Correction of surface flaws and shape defects.
  - Nearly equal elastic and plastic deformation
  - The metals will enter plastic deformation when elastic stress level is satisfied.
  - Yield strength variation calculated by Roberts (1988)

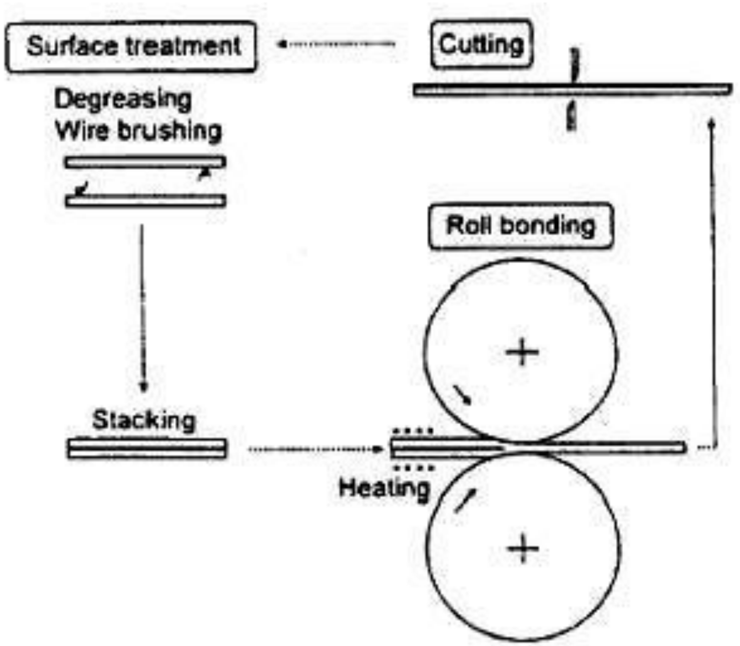
Figure is from John G. Lenard, (2007)

ACCUMULATIVE ROLL BONDING

- INTRODUCTION
  - It is a process of 50 % reduction of a slab during rolling and cutting it into half and then stacking those two pieces on top of each other and repeating the same process over again. It is a type of cold welding process.
  - Surface expansion is needed for surfaces to be adhered
  - High speed brushing before rolling has significant effects while normal brush has no
  - Tzou et al. (2002) states that; reduction, friction factor, interface, tension and bond length are the important parameters to define a strong bond.
  - Zhang and Bay identified the threshold surface expansion.

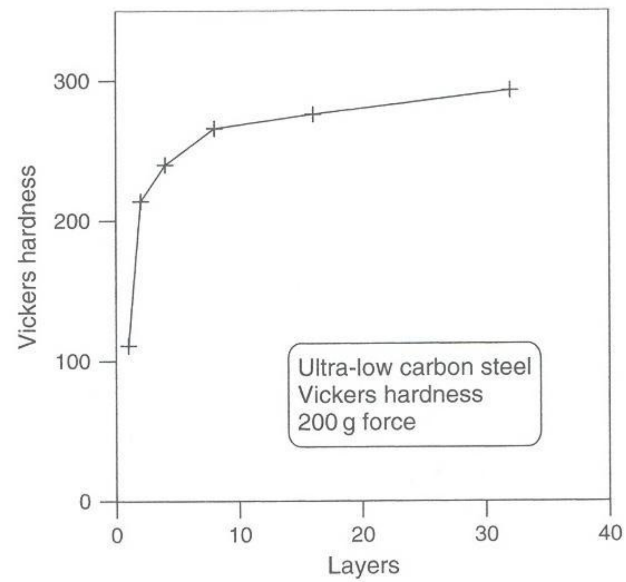
ACCUMULATIVE ROLL BONDING

- INTRODUCTION
  - Warm temperatures gives the best results
  - Ultra fine grains
  - Tensile strength increases
  - Elongation decreases
  - Usually 5 – 8 passes
  - Edge cracking may occur

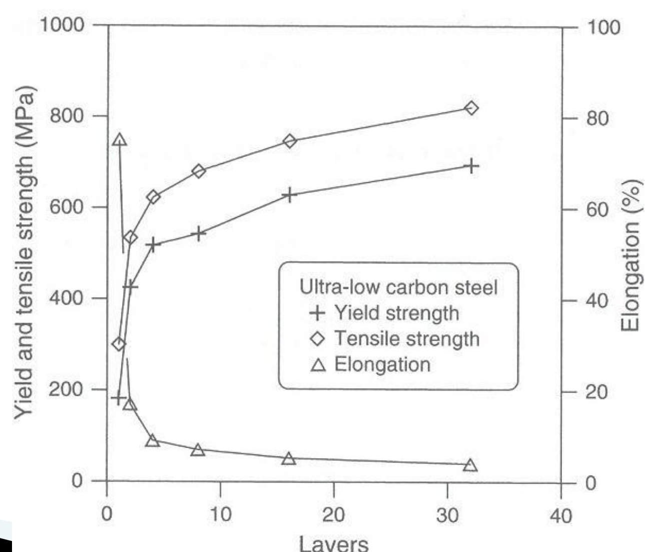


ACCUMULATIVE ROLL BONDING

- MECHANICAL ATTRIBUTES
  - Hardness increases with the number of passes.
  - Up to 100 % increase can be achieved with two layer strip.



- YIELD AND TENSILE STRENGHT



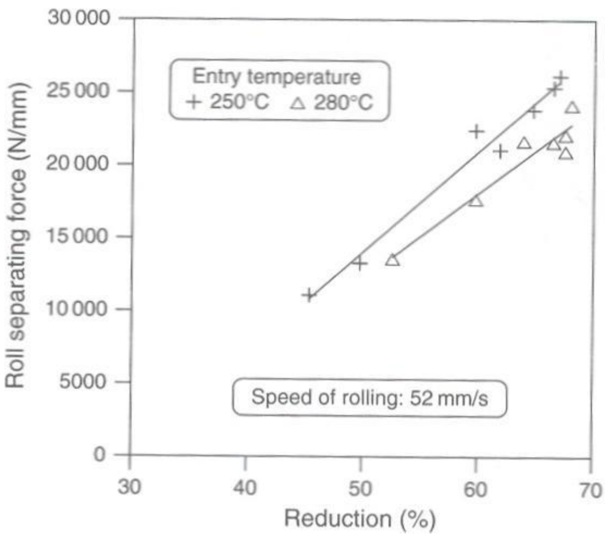
Figures are from John G. Lenard, (2007)

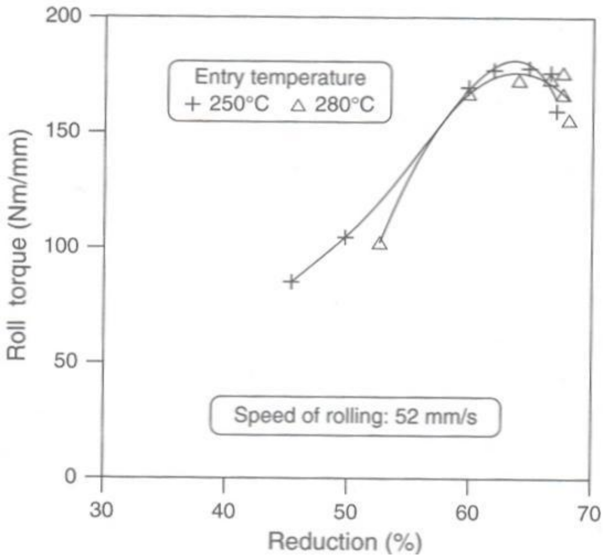
ACCUMULATIVE ROLL BONDING

- THE PHENOMENA AFFECTING THE BONDS
  - Material properties
  - Interfacial pressure
  - Duration of contact
  - Temperature
  - Oxygen or air decrease adhesion
  - Same surface roughness can be achieved manually by brushing
- EDGE CRACKING
  - Up to 16 layers were rolled successfully
  - Edge cracking is the major limitation due to complex stress distribution at the edges
  - Ultra low carbon steels have nearly ideal plastic behavior at 500 C.

ACCUMULATIVE ROLL BONDING

- RESULTS AND DISCUSSION
  - The roll force increase with the reduction
  - The roll torque starts to decrease when the moment arm begins to drop.

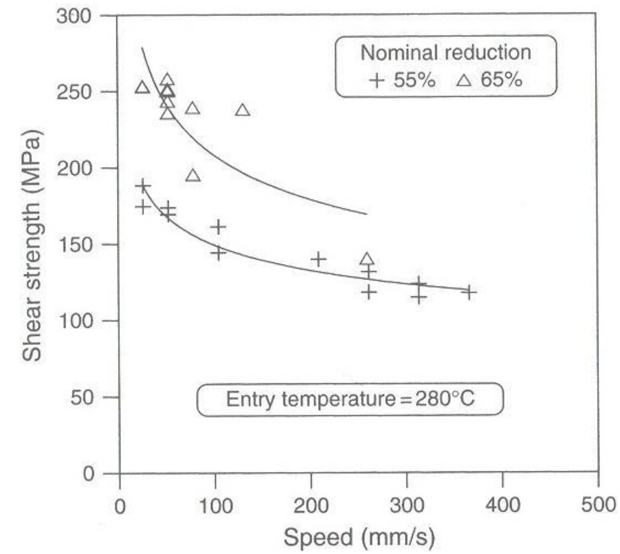




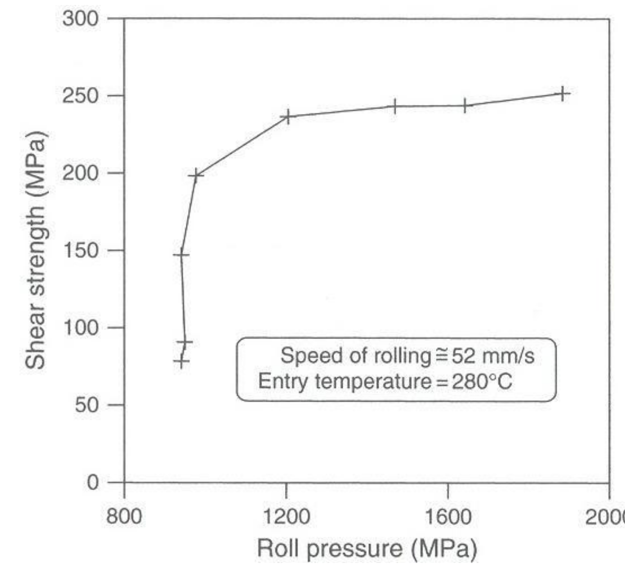
Figures are from John G. Lenard, (2007)

ACCUMULATIVE ROLL BONDING

- SHEAR STRENGHT OF THE BOND
  - Shear strength decrease with rolling speed due to shorter contact time.
  - Highest contact time is achieved with high reduction and low roll speeds



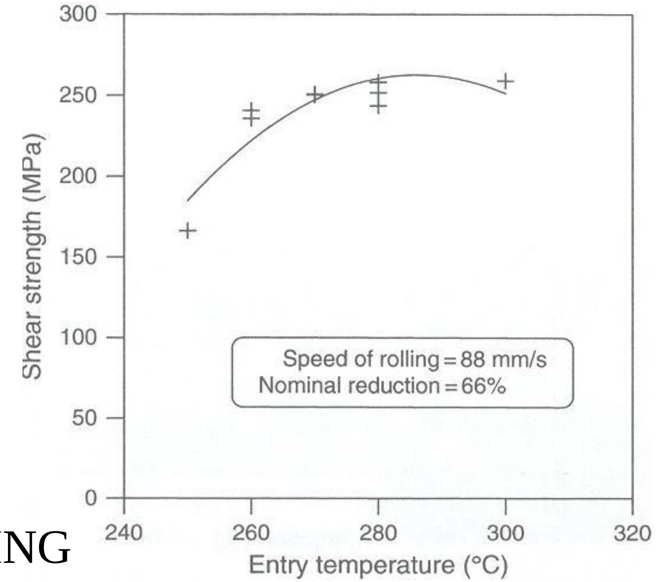
- SHEAR STRENGHT – ROLL PRESSURE
  - Corresponding reductions 40 – 68 %
  - Adhesive forces do not increase beyond one point.



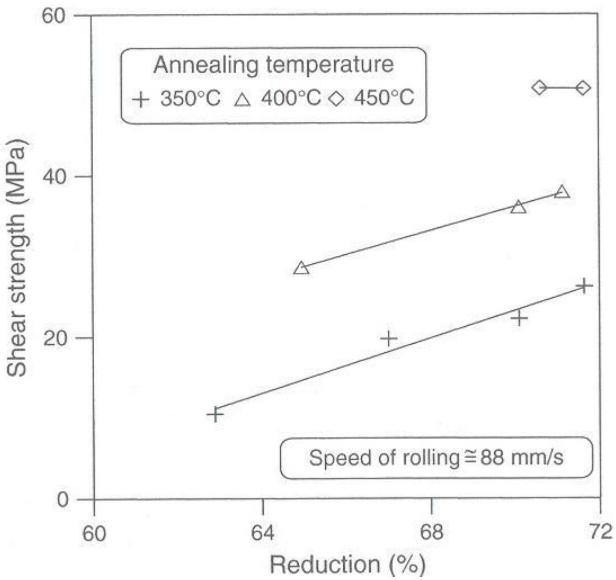
Figures are from John G. Lenard, (2007)

ACCUMULATIVE ROLL BONDING

- EFFECT OF ENTRY TEMPERATURE
  - No more increase in shear strength beyond
  - 280 C.



- EFFECT OF TEMPERATURE ON COLD BONDING
  - Annealing temperatures are shown.
  - Two hours of annealing and then cooling it down
  - Up to 30 % strength of the warm bonding

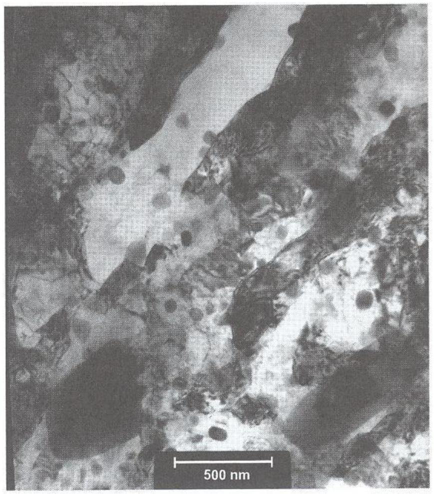


Figures are from John G. Lenard, (2007)

ACCUMULATIVE ROLL BONDING

- TAILORED BLANKS
  - Two different materials welded together with unequal thickness
  - Used widely in automotive industry
  - Different strength and formability on each side.

- ECAP PROCESS AND ROLLING
  - No significant difference on grain size between one pass and three pass 50 % reduction of ECAP.



The microstructure after heat treatment at 420°C for one hour, cooling in the furnace and subjected to one pass of the ECAP process and a rolling pass of 50% reduction. The longitudinal section is shown.

Figure is from John G. Lenard, (2007)

FLEXIBLE ROLLING

- INTRODUCTION

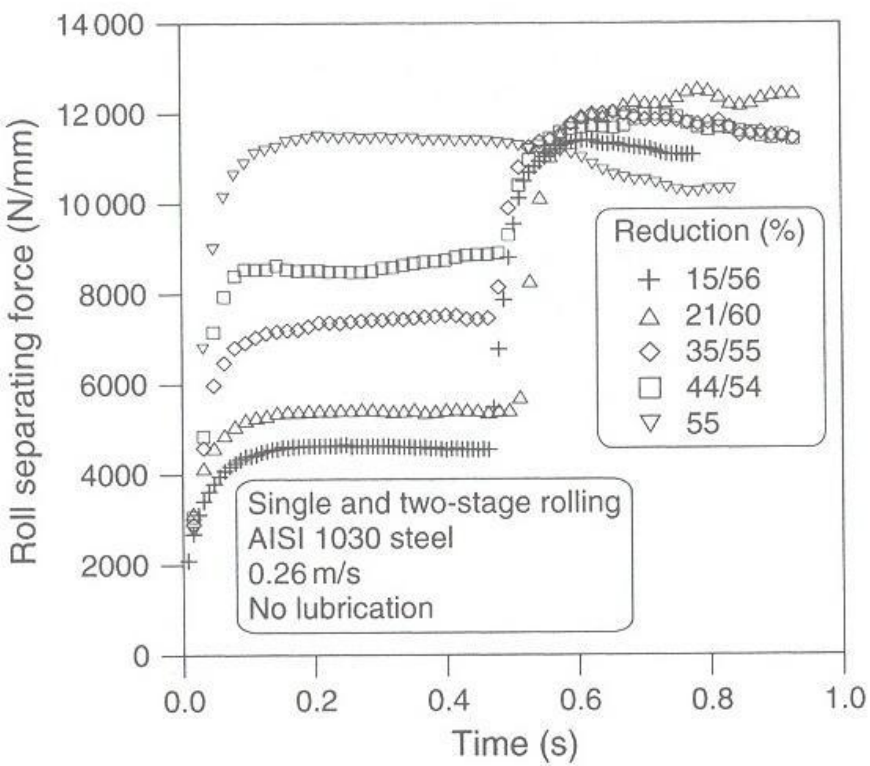
  - Automotive industry is the main reason for development of lightweight metals for different applications
  - One advanced method is tailor – welded blanks for combining two sheets.
  - Chan et al. (2003) concluded that higher thickness ratios resulted lower formability.
  - Kampus and Balic experimented Tailor – welded blank with laser and decided that it is not successful due to high power, fracture on the weld.
  - Ahmetoglu et al. (1995) tested the tailor welded blanks and found out that failure occurs at the flat bottom parallel to the weld line and new design guidelines needed
  - Kopp et al. (2002) described a new technique to produce Tailor welded blanks – *Flexible Rolling*

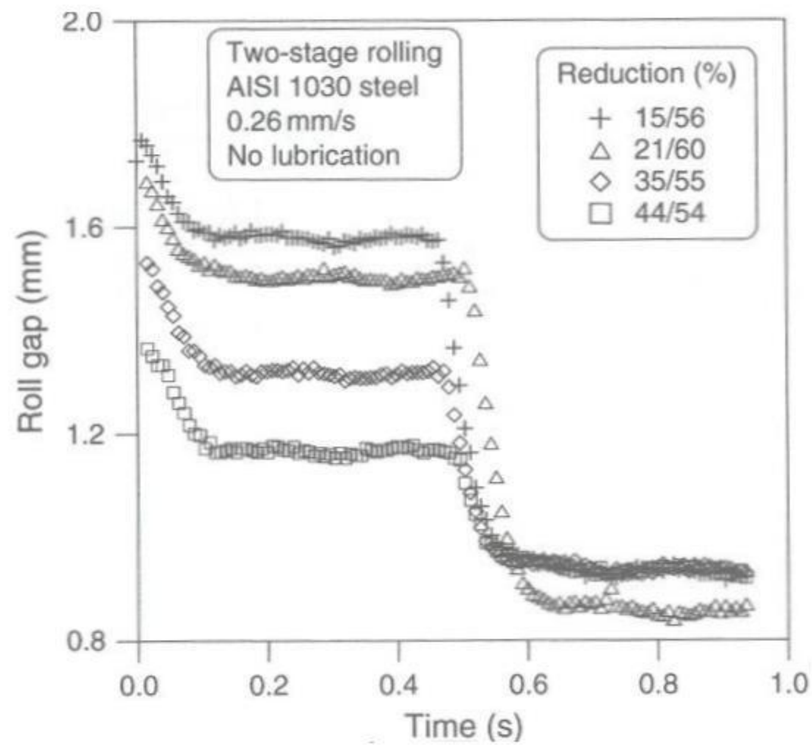
FLEXIBLE ROLLING

- MATERIAL AND THE PROCEDURE
  - Grain sizes are decreased, strength is increased and ductility is decreased.
  - Hirt et al. (2005) stated that 50 % thickness changes are now possible using *Strip Profile Rolling*
  - Roll gap is changed during the pass depending on the desired final product.
  - Data acquisition systems are being used for data collection
  - Process is done without lubrication
  - Fast response of the system and result determination.

FLEXIBLE ROLLING

- ROLL SEPERATING FORCE AND ROLL GAP
  - Metals reaction to cold working can be seen in this two - stage rolling

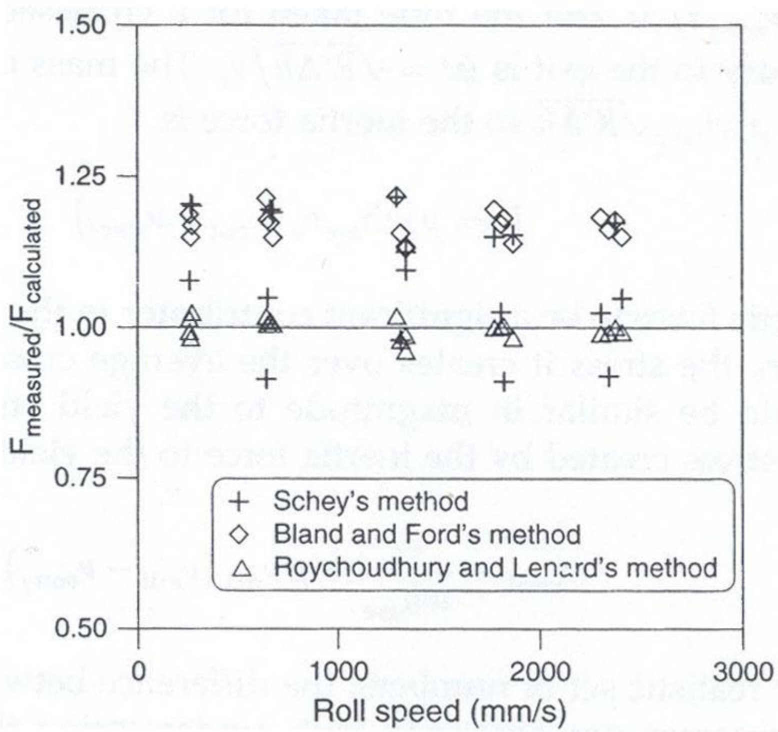




Figures are from John G. Lenard, (2007)

RESULTS AND FUTURE COMPARISON

- COMPARISON OF 3 MATHEMATICAL MODEL'S RESULTS

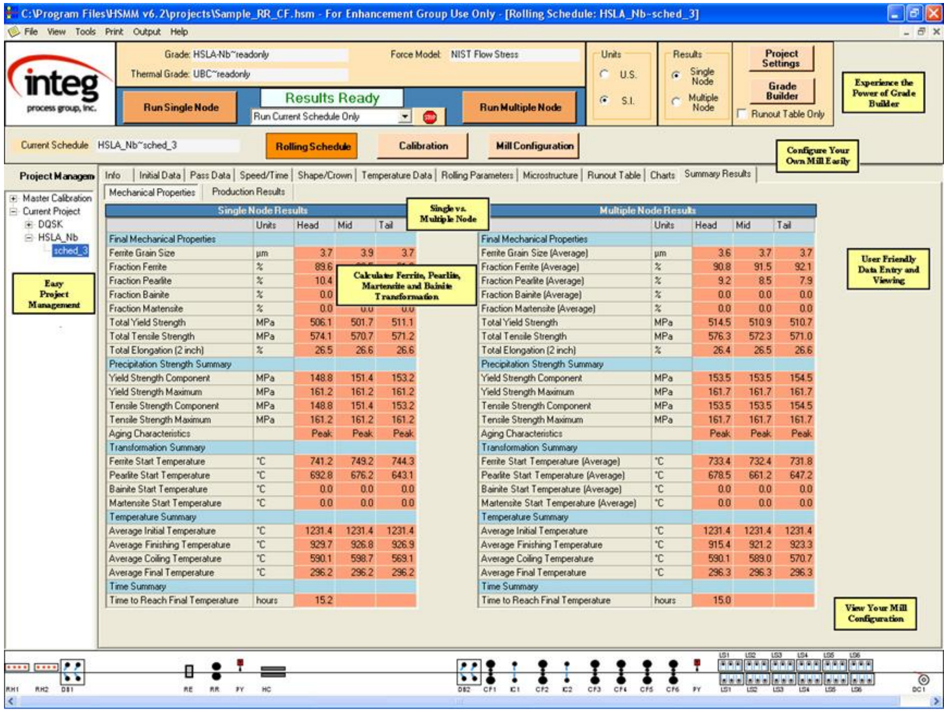


- The ratio of measured and calculated roll separation forces are shown versus different roll rotation speeds.
- In the test low carbon steel is used for cold rolling.
- Different reduction ratios are used between 14 % and 54 %.

Figure is from John G. Lenard, (2007)

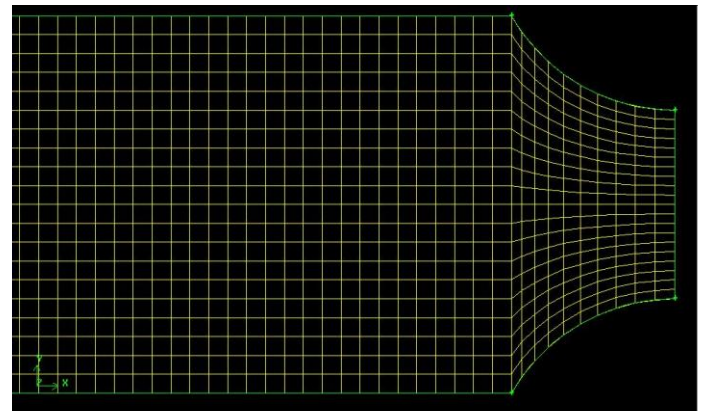
RESULTS AND FUTURE COMPARISON

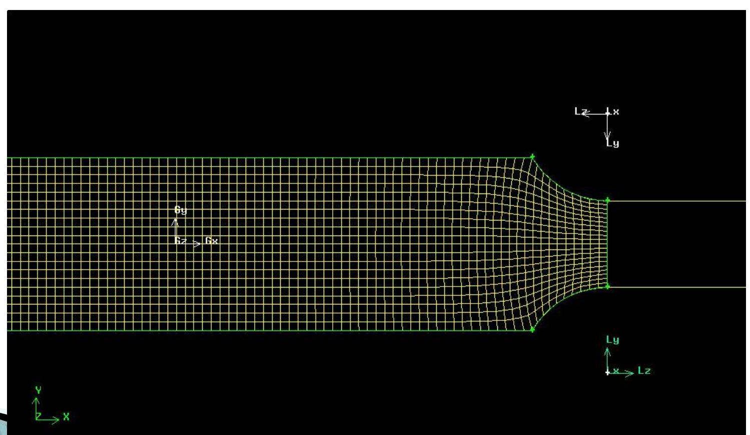
- HSMM
- Inputs of the programe
  - All physical data for rolling mill configuration
  - Material compound
  - Entry temperature
  - Single node or multiple node
- Outputs of the programe
  - Material structure after rolling such as grain size and yield strength.
  - Calculated for head, mid and tail sections seperately
  - Change in width (3D)
  - Exit temperatures or temperature loss due to radation and to the roll seperately

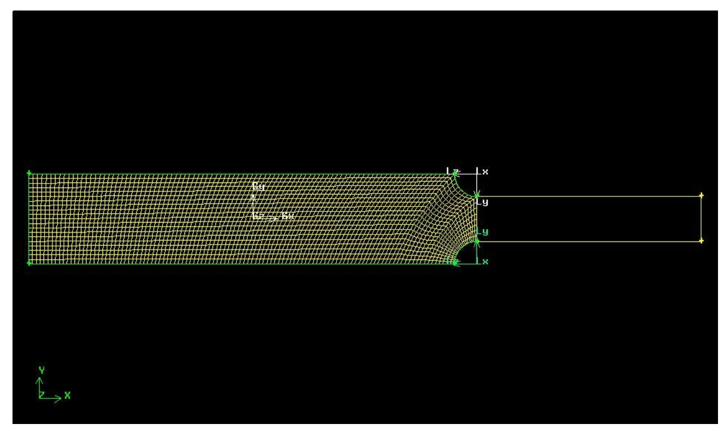


RESULTS AND FUTURE COMPARISON

- CIRCULAR NODE ARRANGEMENT ON THE STRIP
  - FE program FLUENT is used for meshing the strip.
  - Circular shapes are hard in terms of creating ideal node distribution among.
  - Deformation process should also not be forgotten





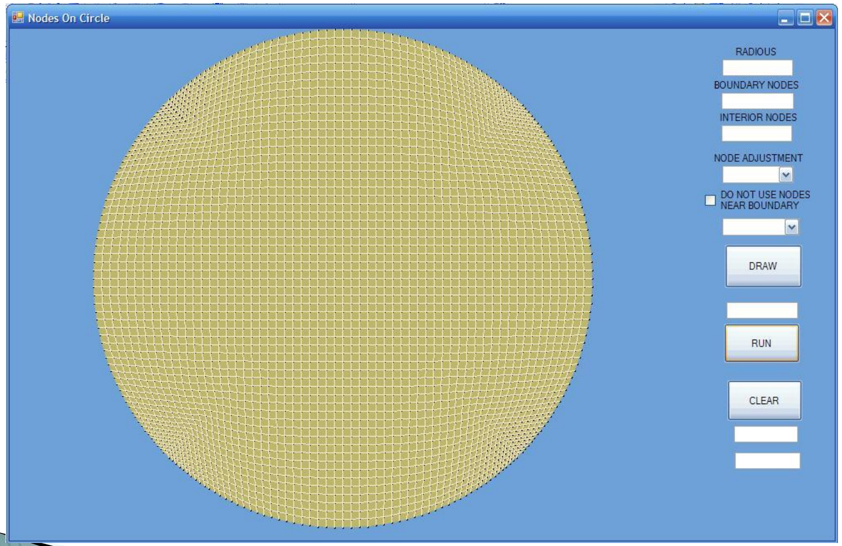


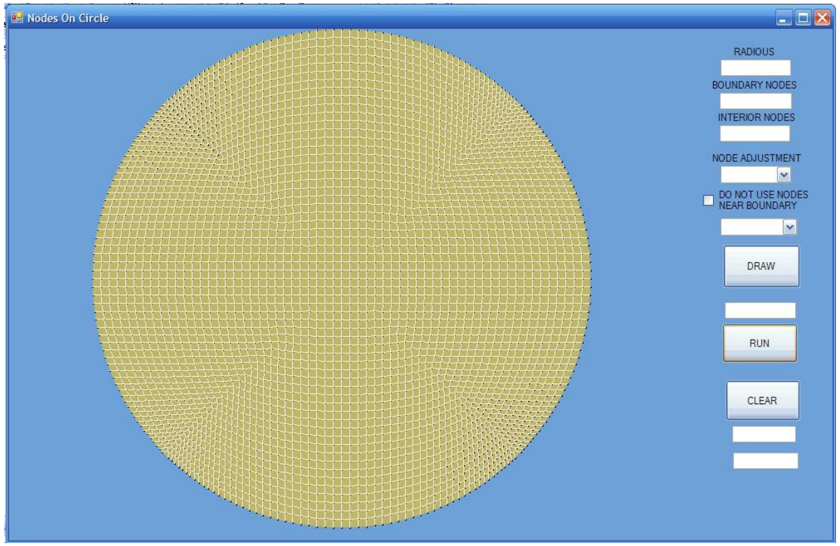
RESULTS AND FUTURE COMPARISON

- CIRCUAR NODE ARRANGEMENT WITH USING BARREL DIFORMATION

$$d - d' = r + kr^3$$

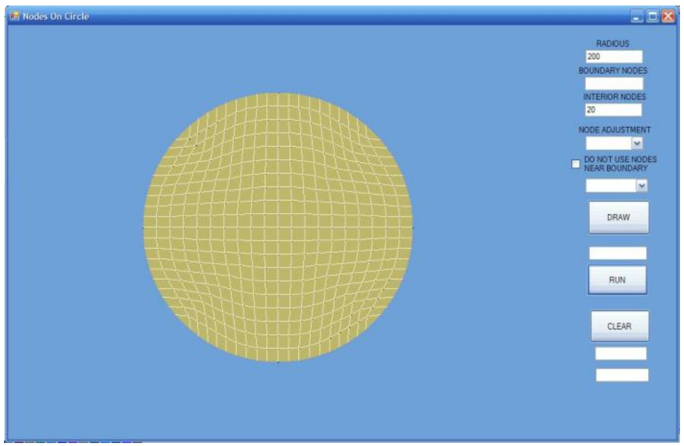
Where d is the original pozition on a square and d' is the new pozition fitted on a circle. k is the constant to be determined. Comparison of tow different values of k is shown below.

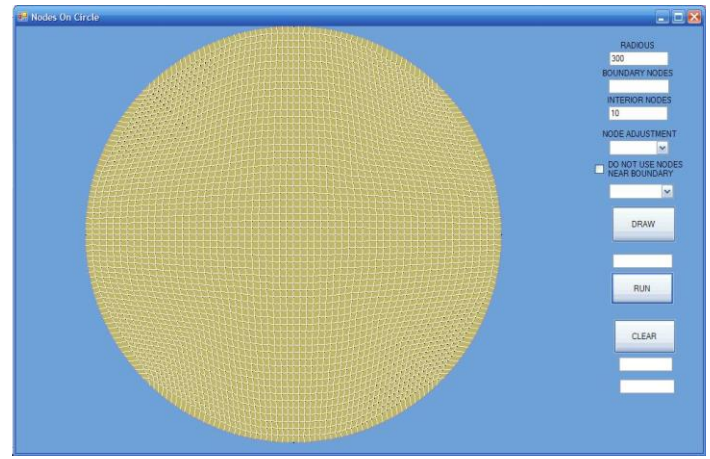


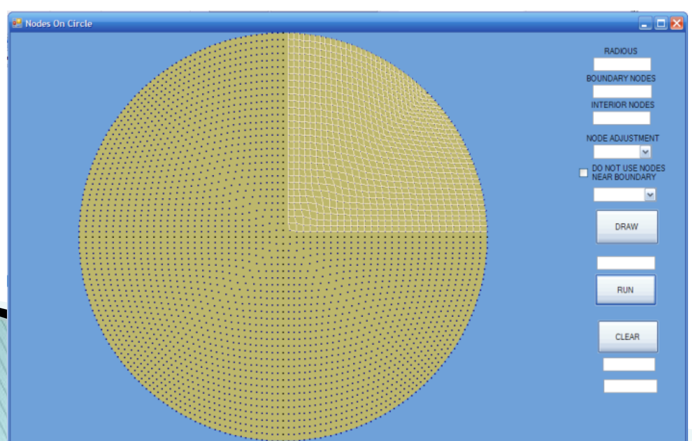


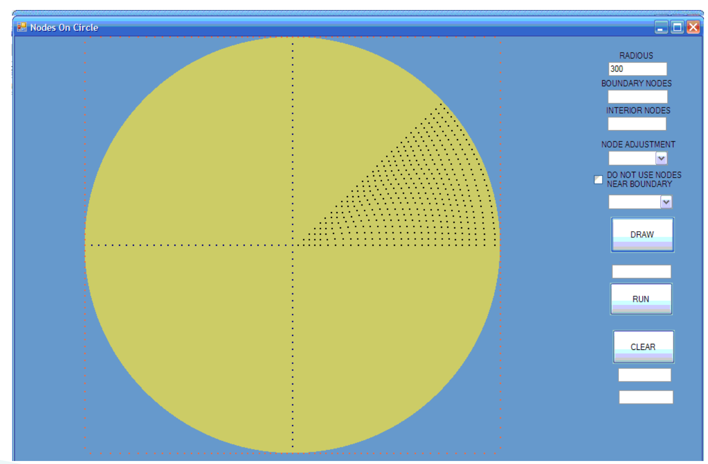
RESULTS AND FUTURE COMPARISON

- CIRCUAR NODE ARRANGEMENT WITH USING BARREL DIFORMATION
  - More examples:









RESULTS AND FUTURE COMPARISON

- DATA FROM THE STORE STEEL COMPANY
  - A chance to compare the future results with industry

ADJUSTMENTS given by »

PS no	SE no	STAND no	DIA roll mm	GROOVE shape no	GAP prior mm	GAP active mm	GAP diff. mm	HOT Hb Si (SQ,DI,XR) mm	HOT Wb mm	DIA eff. mm	RED %	MOTOR nom rpm	MOTOR cal rpm	LOOP m PULL % nom	LOOP m PULL % cal	N.B !!
1	1	1-0	800.0	BX 50		50.00		132.0	200.4	767.5	21.53		154			
2	1	1-0	800.0	TBX 50		10.00		92.00	215.1	794.4	26.39		154			
3	2	1-0	800.0	TBX 15/B		50.00		154.0	109.6	729.2	14.01		154			
4	2	1-0	800.0	TBX 9946		10.00		92.00	160.7	756.0	12.57		154			
5	3	1-0	800.0	TBX 7/B		20.00		112.0	110.5	791.5	20.21		154			
6	3	2-0	650.0	FL 1		72.00		72.00	127.1	690.7	21.57		1344			
7	4	2-0	650.0	EBX 38		30.00		106.0	79.14	612.0	10.22		1344			
8	4	2-0	650.0	FL 1		55.00		55.00	118.0	689.3	20.92		1344			
9	5	2-0	650.0	FL 1		45.00		45.00	123.5	675.8	14.44		1344			
10	5	2-0	650.0	FL 1		40.00		40.00	126.1	665.8	9.17		1344			
11		2-0		BY - PASSING												
12		2-0		BY - PASSING												
13	6	1-1	460.0	FL 1		35.00		35.00	127.9	473.9	11.19		1253			
14	6	2-1	460.0	FL 1		30.00		30.00	129.6	476.4	13.05		1132			
15	7	3-1	460.0	EBX 22		68.00		112.0	32.50	423.0	6.41		1044			
16	7	4-1	460.0	FL 1		27.00		27.00	114.2	479.0	14.93		942			-N
17	7	6-1	460.0	FL 1		24.00		24.00	115.4	472.6	10.24		851			-N
18	8	7-1	460.0	EBX 22		59.00		103.0	25.67	421.2	4.81		453			-N
19	8	8-1	460.0	FL 1		22.00		22.00	104.6	475.8	12.63		763			-N
20	9	9-1	460.0	EBX 22		56.00		100.0	22.60	418.0	1.92		393			-N
21	9	10-1	460.0	FFL 1		20.00		20.00	101.2	472.7	10.33		699			-N

COMPUTATIONAL SIMULATION

- GOVERNING HEAT TRANSFER EQUATION

$$\Delta T = \frac{\sigma_{fm}}{\rho c_p} \ln \frac{1}{1-r} - 60\alpha \sqrt{\frac{r}{h_{entry} R}} \left(T_{strip} - T_{roll} \right) \left[\left(1-r \right) \pi \rho c_p N \right]^{-1}$$

- GOVERNING EQUATION OF EQUILIBRIUM OF FORCES

$$\frac{d\left(\sigma_x h\right)}{dx} + p\frac{dh}{dx} \mp 2\mu p = 0$$

$$\frac{dp}{dx} \pm 2\mu \frac{p}{h} = \frac{2k}{h}\frac{dh}{dx} + \frac{d(2k)}{dx}$$

COMPUTATIONAL SIMULATION

- LOCAL RADIAL BASIS FUNCTION COLLOCATION METHOD
  - 5 node based system with 4 neighbors each
  - Approximation: $\varphi(x) = \sum_{i=1}^{5} c_i \psi_i(r)$, where $\vec{r} = (x, y)$, φ is an arbitrary function
  - c_i are the constants to be determined
  - $\psi(r)$ is the trial function defined as: $\psi(r) = \sqrt{(x - x_i)^2 (y - y_i)^2 + c^2}$ for $c > 0$
  - $\psi(r)$ becomes a symmetric 5x5 matrix and needs to be non-singular in order to calculate the necessary coefficients depending on the boundary conditions

CONCLUSIONS

- Flat rolling process
- Plasticity of material during rolling and compression
- Roll deformation
- Roll separating force, roll pressure, shear stress, friction
- Friction factor and coefficient of friction
- Schey’s model, sim’s model, Orowan model and refinements to Orowan model
- Temperature gain and loss during rolling
- Static, dynamic and metadynamic recrystallization
- Roll torque and power calculations
- Influence of physical quantities on rolling
- Temper, accumulative roll bonding, flexible rolling
- Comparison of some calculations
- Base of computational simulation to be done

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