MATHEMATICAL AND PHYSICAL MODELING OF THE FLAT ROLLING PROCESS

by

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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
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 \(\mu\)
  - 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 \(\Delta h\) in mm.
  - Shear stress \(\tau\) in Pa.
  - The angle between the vertical lines is \(\phi\)
  - 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 $h_{\text{ave}} = \frac{(h_{\text{entry}} - h_{\text{exit}})}{2}$ 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)

  \[ h_{\text{min}} = \frac{3.58 D \mu \sigma_{fm}}{E} \]

  where \( D \) is the roll diameter in mm, \( E \) is the elastic modulus in Pa, \( \sigma_{fm} \) is the average flow strength in Pa, and \( \mu \) is the coefficient of friction. Claimed that in reality this does not exist.

  - Edge cracking

  - Alligating

Figures are from John G. Lenard, (2007)
ROLLING MILL

HITCHCOOK’S RADIUS

- Elasticity of the roll is considered

- Hitchcock’s equation (1935):

\[ R' = R \left[ 1 + \frac{16(1 - \nu^2)}{\pi E \Delta h} P_r \right] \]

where \( R' \) is the flattened but still circular roll radius in mm, \( R \) is the original roll radius in mm, \( \nu \) is the Poisson’s ratio, \( E \) is the Young’s modulus of the roll in Pa, \( \Delta h \) 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:

\[ \Delta = \frac{PL^3}{EI} + 0.2 \frac{PL}{AG} \]

where:
- \( P \) 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,
- \( A \) is the cross-sectional area in mm².

- Rowe (1977) calculated the maximum deflection as:

\[ \Delta = \frac{P\bar{L}^2(5L + 24c)}{6\pi ED^4} + \frac{P\bar{L}}{2\pi GD^2} \]

where:
- \( \bar{L} \) is the half of the bearing length in mm,
- \( D \) is the diameter of the roll in mm,
- \( c \) is the length of the roll in mm.
ROLL PRESSURE AND ROLL SEPARATING 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

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

Figure is from John G. Lenard, (2007)
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
COEFFICIENT OF FRICTION

- Reason for the process to start and to move forward
  
  $$\mu_{\text{min}} = \tan \phi_{\text{bite}}$$

- 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

Figures are from John G. Lenard, (2007)
LUBRICANT

- Oil-water emulsions are the most common lubricant.

- The viscosity: 
  \[ \tau = \eta \dot{\gamma} \quad \mu = \frac{\eta}{\rho} \]

  \( \eta \) is the dynamic viscosity in Pa.s, \( \mu \) is the kinematic viscosity in m²/s, \( \dot{\gamma} \) is the shear strain rate, \( \rho \) is the density.

- Viscosity – Pressure: 
  \[ \eta = \eta_0 \exp(\gamma p) \quad \eta = \eta_0 \left(1 + C p\right)^n \]

  \( \eta_0 \) is the viscosity under atmospheric pressure and \( \gamma \) is the pressure-viscosity coefficient and \( p \) is the pressure. \( C \) and \( n \) are constants.

Figures are from John G. Lenard, (2007)
**FRICION FACTOR**

\[ \tau = mk \quad 0 \leq m \leq 1 \]

- 1-D equation could be written as;

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

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

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

- The relative velocity is given;

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

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

Figure is from John G. Lenard, (2007)
SCHEY’S MODEL

- Schey’s model, roll separating force per unit with:

\[ P_r = 1.15 Q_p \sigma_{fm} L \]

- Average flow strength; \( \sigma_{fm} \) (in Pa) is obtained by:

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

\( Q_p \) is the pressure intensification factor which is roll pressure divided by average flow strength \( \frac{p}{\sigma_{fm}} \), \( \varepsilon_{max} \) 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

Figure is from John G. Lenard, (2007)
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.
OROWAN’S MODEL

1 - Dimensional equilibrium based model;

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

\( \sigma_x \) is the stress in the direction of rolling and \( \overline{p} \) 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:

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

\( k \) is the yield strength under pure shear.
MATHEMATICAL MODELING OF ROLLING

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)

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

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

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

Figure is from John G. Lenard, (2007)
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, \( \rho \) is the density of the strip in kg/m\(^3\) and \( c_p \) is the specific heat of strip in J/kg\(^\circ\)C.
  
  - Temperature rise by Roberts (1983) is:
    \[ \Delta T_{gain} = \frac{\sigma_{fm}}{\rho c_p} \ln \left( \frac{1}{1 - r} \right) \]
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:

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

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

\[ \frac{T_{\text{roll}} - T_0}{T_{\text{strip}} - T_0} = \alpha \sqrt{\frac{t}{k c_p \rho}} \]

\( T_{\text{roll}} \) 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 °C) above recrystallization occurs is;

\[
\]

- 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.

Figure is from keytometals.com
STATIC RECRYSTALLIZATION

- Time for 50% recrystallization is:

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

\( \varepsilon \) is the strain, \( D_\gamma \) is the austenite grain size prior to deformation in \( \mu \text{m} \), \( Z \) is the Zener-Hollomon parameter defined as:

\[ Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \]

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

Figure is from John G. Lenard, (2007)
RECRYSTALLIZATION

- STATIC RECRYSTALLIZATION

- Recrystallized grain size:

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

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

- Time for \( X \% \) recrystallization in seconds is:

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

\( t_x \) 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, \( D_\gamma \) 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:

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

\( \eta_m, \eta_t \) are the efficiencies of the driving motor and the transmission. \( P_n \) is the power loss on bearings due to friction in Watts.
THE SENSITIVITY OF ROLL SEPARATING FORCE TO COEFFICIENT OF FRICTION AND REDUCTION

- Predicted with using Schey’s and refined 1D model

Figure is from John G. Lenard, (2007)
INFLUENCE OF PHYSICAL QUANTITIES

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

Figures are from John G. Lenard, (2007)
INFLUENCE OF PHYSICAL QUANTITIES

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

Figures are from John G. Lenard, (2007)
INFLUENCE OF PHYSICAL QUANTITIES

ROLL PRESSURE DISTRIBUTION

Figure is from John G. Lenard, (2007)
INFLUENCE OF PHYSICAL QUANTITIES

- THE CRITICAL STRAIN

Figure is from John G. Lenard, (2007)
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 STRENGTH

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 STRENGTH 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 STRENGTH – 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.

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 in 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.
ROLL SEPARATING FORCE AND ROLL GAP

Metals reaction to cold working can be seen in this two-stage rolling.
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 program:
- All physical data for rolling mill configuration
- Material compound
- Entry temperature
- Single node or multiple node

Outputs of the program:
- Material structure after rolling such as grain size and yield strength.
- Calculated for head, mid and tail sections separately
- Change in width (3D)
- Exit temperatures or temperature loss due to radiation and to the roll separately
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

- CIRCULAR NODE ARRANGEMENT WITH USING BARREL DISFORMATION

\[ d - d' = r + kr^3 \]

Where \( d \) is the original position on a square and \( d' \) is the new position fitted on a circle. \( k \) is the constant to be determined. Comparison of two different values of \( k \) is shown below.
RESULTS AND FUTURE COMPARISON

- CIRCULAR NODE ARRANGEMENT WITH USING BARREL DISTORTION
  - More examples:
## RESULTS AND FUTURE COMPARISON

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

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COMPUTATIONAL SIMULATION

GOVERNING HEAT TRANSFER EQUATION

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

GOVERNING EQUATION OF EQUILIBRIUM OF FORCES

\[ \frac{d(\sigma_x h)}{dx} + p \frac{dh}{dx} \pm 2\mu p = 0 \]

\[ \frac{dp}{dx} \pm 2\mu \frac{p}{h} = \frac{2k}{h} \frac{dh}{dx} + \frac{d(2k)}{dx} \]
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 \( \vec{r} = (x, y) \), \( \varphi \) 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
REFERENCES


REFERENCES


