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STEADY STATE MODEL FOR HELWAN REVERSING FOUR HIGH MILL COLD ROLLING STAND

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ABSTRACT

The cold rolling process is one of the important processes in the Egyptian iron and steel industry. For thorough understanding of the process mechanics and the effect of its key operating variables on its performance, it has to be modelled. Furthermore, modelling of the process helps in building a steady state optimization program and achieving high level control strategies aiming at improving its performance.

A complete steady state modelling scheme has been applied to the 1200 mm - reversing four high mill stand of Helwan Iron and Steel Company. The mathematical model covers the rolling force, the specific torque, the forward slip of the strip at the bite exit, the deflection of the rolls, the maximum stress induced in the roll and the efficiency of the rolling process. Strip thickness of 2 mm and percentage reduction from 10 to 50 % have been considered.

1. INTRODUCTION

A number of mathematical models have been developed over the last two decades as an attempt to describe the cold rolling process. Because of the complexity of the conditions and the number of variables involved, simplifying assumptions have been made to permit the theoretical analysis of the process. Mathematical expressions, which theoretically relate the various rolling parameters, are generally referred to as models of the rolling process.

The models serve a number of purposes such as mill design and evaluation of the mill stand characteristics. In addition, they are the basis of controlling the cold rolling mills and operating them in an optimal manner. The models of the rolling process may be dynamic [1,2] or static(steady state) [3-7] .

The steady state models are considered in this study since they suit the

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existing stage of the local industries. When a process is in continuous operation such as the strip cold rolling one, it is of vital importance to set the process variables in an optimal manner for the purpose of safety, quality and energy saving [8,9] .

The developed models are applied to the cold rolling stand of Helwan Iron and Steel Company as a case study. A strip thickness of 2mm and one meter width is considered with 10, 20, 30, 40 and 50 % reduction in thickness.

2. ASSUMPTIONS

The following assumptions are used in the development of the steady state models of the cold rolling process:

(a) The density of the strip is constant during rolling
(b) The yield strength of the strip is constant along the arc of contact
(c) The strip is homogeneously compressed during its plastic deformation
(d) Lateral spreading of the strip is neglected
(e) The coefficient of friction is uniform along the arc of contact
(f) Elastic deformation of the strip in the roll bite is neglected
(g) The acceleration of the strip in the roll bite is neglected
(h) Thermal effects are neglected
(i) The work rolls speeds are uniform and equal

3. STEADY STATE MODEL FOR A FOUR HIGH COLD ROLLING MILL

The performance of a single stand cold rolling mill is determined by the assignment of the average compressive yield strength of the strip in the bite, length of arc of contact, rolling force, rolling torque, strip forward slip, roll deflection, roll induced stress, rolling power and rolling efficiency.

3.1 Yield Strength of the Strip

It is necessary for predicting the rolling force to know the yield strength of the rolled strip as function of the percentage reduction(strain hardening) [3,6,10] . The strip yield strength increases nonlinearly with the reduction [10] . Since it is convenient for computer work to use mathematical rather than graphical models, a second order polynomial model was fitted using an available computer package at Cairo University [11] . On the other hand, the average compressive yield strength in the roll bite corresponds to half the reduction given during the rolling pass [6] . The model is given by:

$$\sigma_y(r/2) = 247.0 + 781.4\, r - 157.8\, r^2 \qquad (1)$$

where $\sigma_y(r/2)$ is the average yield strength and r is the reduction defined as:

$$r = 1 - \frac{\text{exit strip thickness}}{\text{entry strip thickness}} \qquad (2)$$

3.2 Average Compressive Yield Strength

The compressive yield strength of the rolled strip increases from the entry to the exit plane of the roll bite according to the stress-strain curve. An average value may be taken at half the reduction given to the strip [7] . In absence of tensile stresses in the strip, the average compressive yield strength σ_c is given by [6,7] :

$$\sigma_c = 1.15\,\sigma_y(r/2) \qquad (3)$$

where $\sigma_y(r/2)$ is given by Eg.(1).

If σ_1 and σ_2 are the entry and exit tensile stresses in the strip respectively, σ_c is then function of σ_1, σ_2, r and $\sigma_y(r/2)$. That is [7] :

$$\sigma_c = 1.15\,\sigma_y(r/2) - \frac{\sigma_1 + \sigma_2(1-r)}{2-r} \qquad (4)$$

3.3 The Length of the Arc of Contact

The arc of contact between the roll and the rolled strip consists of three zones:the first due to the strip deformation assuming rigid rolls, the second due to the roll flattening and the third due to the friction in the roll bite. The total effective length of the arc of contact between the strip and each roll, L_e is given by [6,7] :

$$L_e = \sqrt{0.5Dtr} + 1.08\sqrt{fD/E} + \frac{0.583\,\mu Df(2-r)}{Et(1-r)} \qquad (5)$$

where D is the work roll diameter, t is the entry strip thickness, f is the specific rolling force, E is the elastic modulus of the roll material and μ is the coefficient of friction in the bite.

3.4 The Rolling Force

The specific rolling force(force per unit width of the strip) f may be considered as the product of the average compressive yield strength of the strip σ_c and the effective length L_e of the arc of contact [6,7] . That is

$$f = \sigma_c L_e \qquad (6)$$

For a strip of width b, combining Eqs.(4),(5) and (6) gives the rolling force F as

$$F = b\left\{\left[\frac{1.08\sqrt{D/E} + \sqrt{1.166D/E + \sqrt{8Dtr}\left(\frac{1}{\sigma_c} - \frac{0.583\mu D(2-r)}{Et(1-r)}\right)}}{2\left(\frac{1}{\sigma_c} - \frac{0.583\mu D(2-r)}{Et(1-r)}\right)}\right]^2\right\} \qquad (7)$$

3.5 The Specific Rolling Torque

The specific rolling torque is the torque per unit strip width applied on each spindle and required to perform the strip rolling to the required reduction. If τ_R is the specific torque of the roll bearings, the specific rolling torque for each roll is given by [6,7,15] :

$$\tau = \frac{Dt\sigma_c}{2}\left[r\left(1+\frac{\sigma_2}{\sigma_c}\right) + \frac{\sigma_1-\sigma_2}{\sigma_c}\right] + \tau_R \qquad (8)$$

3.6 The Forward Slip of the Strip at the Bite Exit

The forward slip is defined as the ratio between the excess velocity of the strip at the bite exit and the peripheral velocity of the work rolls. As function of the strip tensile stresses σ_1 and σ_2 (see Fig.1), compressive strength σ_c, specific rolling force f and reduction r, the forward slip ν is given by [3,7,13] :

$$\nu = \frac{r}{2.25(1-r)} \left\{ 1 - \frac{t\sigma_c}{2\mu f} \left[r\left(1+\frac{\sigma_2}{\sigma_c}\right) + \left(\frac{\sigma_1-\sigma_2}{\sigma_c}\right) \right] \right\}^2 \qquad (9)$$

3.7 The Deflection of the Rolls

The roll deflection occurs as a result of both bending and shear strains under the effect of the rolling force. Referring to Fig.1, the deflection δ of the roll at a point of distance X from the centre of the neck bearing is related to the rolling force F and the back up roll parameters through the equation [4,7,16] :

$$\delta = \frac{F(X-n)}{24EI} \left[\frac{(X-n)^3}{W} + L^2 + 2Wn - 2X(X+n) \right] + \frac{2F}{WGD_b^2} \left[X(L-X) - n(L-n) \right] \qquad (10)$$

where W is the length of the roll barrel, I is the area moment of inertia of the roll cross-sectional area, L is the distance between the centres of the roll neck bearings, n is the distance between the centre of the roll neck bearing and the roll edge(see Fig.1), G is the modulus of rigidity of the roll material and D_b is the back up roll diameter.

3.8 The Roll Stresses

The stress induced in the work roll is a combined bending and torsion stresses. Using the Hencky-von Mises theory [17] , the maximum roll stress τ_m is given by:

$$\tau_m = \sqrt{\sigma_b^2 + 3\tau_t^2} \qquad (11)$$

where the bending stress σ_b and the torsion stress τ_t are given by [4,10, 16] :

$$\sigma_b = 2.5\ FL/\ D^3$$

and

$$\tau_t = 2.475\ \sqrt{tr}\ /\ D^{2.5}$$

3.9 The Power Required for Cold Rolling

The power used in the cold rolling process is dissipated in the deformation of the strip, overcoming the mechanical losses in the roll bearings, pinions, between rolls, between rolls and strip and pulling the strip through the rolls.

The power required to deform the strip, dissipated in the roll neck bearings and utilized in pulling the strip by the coiler and decoiler systems is given as [4,7,9,13] :

$$P = 5.18 \times 10^{-5}\ FN\ \sqrt{Dtr} + 10.47 \times 10^{-5}\ F\mu_1 Nd + 5.236 \times 10^{-5}\ DNbt(1-r)(\sigma_1-\sigma_2) \quad \text{kW} \qquad (12)$$

where P is the minimum power required for rolling of the strip, N is the roll speed(rev/min), d is the roll neck diameter and μ_1 is the coefficient of friction in the roll bearings.

3.10 The Process Efficiency

The efficiency of a rolling mill stand is defined as the ratio between the energy required to deform the strip minus the energy supplied by the strip tensile forces and the energy supplied by the drive spindles [7] . Roberts [6,7] showed that the rolling efficiency η is related to the other rolling parameters through the relationship:

$$\eta = \frac{(1-r)(1+\nu)\ \left\{1.15\ \sigma_y (r/2)\ \ln\left[1/(1-r)\right] + \sigma_1-\sigma_2\right\}}{r\ \sigma_c + \sigma_1 - (1-r)\sigma_2} \times 100 \qquad (13)$$

4. CASE STUDY: MODELLING OF HELWAN COLD ROLLING STAND

4.1 Stand Specifications

Helwan cold rolling stand is a reversing four high mill having the following specifications [18,19] :

- -Diameter of work rolls: 400 mm
- -Diameter of back up rolls: 1300 mm
- -Length of roll barrel: 1200 mm
- -Rolling speed: up to 15 m/s
- -Entry strip thickness: up to 3 mm
- -Strip width: up to 1020 mm
- -The work rolls are supported by roller bearings and the back up rolls are supported by oil film bearings
- -Coefficient of friction in the roll bite: 0.04-0.055 [14]
- -Coefficient of friction in the roller bearings: 0.002-0.003 [4,13]

4.2 Stand Modelling

The steady state model represented by Eqs.(1) through (13) is applied on Helwan cold rolling stand with the specifications presented before and the following conditions:

- -Rolled strip: steel strip of 2 mm thickness and 1000 mm width (elastic modulus = 18 x 10^{10} N/m^2 [10])
- -Entry and exit tensile stresses: σ_1 = 10 and σ_2 = 40 MN/m^2

Using Cairo University-ICL mainframe computer, the rolling force, rolling torque,forward slip at bite exit, roll deflection, roll stress, rolling power and process efficiency were programmed in FORTRAN and the results are given in Table 1 for 10, 20, 30, 40 and 50 % reduction in the strip thickness.

5. DISCUSSIONS

(a) The steady state model presented in the paper clarified the mechanics of the cold rolling process for purpose of understanding the effect of the different variables, optimizing its operation and its control.
(b) The rolling force increases 335 % for reduction increase from 10 to 50 %.
(c) The rolling torque increases 3592 % for reduction increase from 10 to 50 %.
(d) The forward slip increases 95 % for reduction increase from 10 to 50 %
(e) The roll deflection increases 335 % for reduction increase from 10 to 50 %.
(f) The maximum stress in the roll increases 335 % for reduction increase from 10 to 50 %.
(g) The rolling power increases 337 % for reduction increase from 10 to 50 %.
(h) The process efficiency decreases 25.6 % for reduction increase from 10 to 50 %.
(i) The study carried out at Cairo University covered a strip thickness range from 0.5 to 3 mm and different levels of entry and exit tensile stresses [9] .
(j) Experimental verification of the theoretical results obtained is required through supplying the cold rolling stand of Helwan with accurate measuring instruments.

6. REFERENCES

1. Jortner,D., "Dynamics of Rolling Mills-Mathematical models and Experimental Results", Iron and Steel Engineer, p.35,Dec.(1977)
2. Wallace,J., "Fundamental of Strip Mill Automatic Gage Control Systems", ibid, p.193, Sept.(1964)
3. Underwood,L., "The Rolling of Metals-Theory and Experiment", Chapman and Hall Ltd.,(1950)
4. Larke,E., "The Rolling of Strip, Sheet and Plate", ibid,(1963)
5. Schultz,R. and Smith,A., "Determination of a Mathematical Model for Rolling Mill Control", Iron and Steel Engineer, p.127, May (1965)
6. Roberts,W., "A Simplified Cold Rolling Model", ibid, p.75, Oct. (1965)
7. Roberts,W., "Cold Rolling of Steel",Marcel Dekker Inc., (1978)
8. Hassan,G.A., "Steady State Optimal Setting of the Plastics Extrusion Control Variables", Bulletin of the Fac.of Eng., Cairo Univ., 2,(1983)
9. Ibrahim,G.Y., M.Sc. Thesis, Cairo University,(1983)
10. Rao,S. and Kumar,A., "Optimization of Cold Rolling by Nonlinear Programming", Trans.of ASME, J.of Eng.for Industry, 100, p.186, May(1978)
11. Hassan,G.A., Ph.D. Thesis, University of Bradford, U.K.,(1979)
12. Roberts,W.,Bentz,R. and Litz,D., "Cold Rolling Low Carbon Steel Strip to Minimum Gage", Iron and Steel Engineer, p.77,Aug.(1970)
13. Tselikov,A.,Nikitin,G. and Rokotyan,S., "The Theory of Lengthwise Rolling", MIR Pub., (1981)
14. Vojnovic,S.,Somers,R. and Roberts,W., "The Laboratory Evaluation of Lubricants used in the Cold Rolling of Steel Strip",Iron and Steel Engineer, p.95, May(1964)

15. Hessnberg,W. and Sims,R., "The Effect of Tension on Torque and Roll Force in Cold Rolling", J. Iron and Steel Institute, p.168, (1951)
16. Tselikov,A. and Smirnov,V., "Rolling Mills",Pergamon Press(1965)
17. Soderberg,G., "Working Stresses", Trans.of ASME, 55,3, p.A-107, (1935)
18. Tselikov,A. and Zyuzin,V., "Modern Development of Rolling Mills", MIR Pub., (1975)
19. Private Communications with the Iron and Steel Company, Helwan, Egypt.

7. NOMENCLATURE

b	Strip width,m
d	Roll neck diameter, m
D	Work roll diameter, m
D_b	Back up roll diameter, m
E	Elastic modulus of roll material, N/m^2
f	Specific rolling force, N/m
F	Rolling force, N
G	Modulus of rigidity of roll material, N/m^2
I	Area moment of inertia, m^4
L	Distance between centres of the roll neck bearings, m
L_e	Effective length of the arc of contact, m
n	Distance between roll neck bearing centre and barrel edge, m
N	Roll speed, rev/min
P	Rolling power, kW
r	Reduction in strip thickness
t	Entry thickness of the strip, m
W	Length of roll barrel, m
X	Distance along the roll, m
δ	Roll deflection at distance X, m
η	Rolling efficiency
μ	Coefficient of friction in the roll bite
μ_1	Coefficient of friction in the bearings
ν	Forward slip
σ_b	Bending stress, N/m^2
σ_c	Average compressive yield strength, N/m^2
σ_y	Yield strength of the roll material, N/m^2
σ_1, σ_2	Entry and exit tensile stresses in the strip, N/m^2
τ	Specific rolling torque, Nm/m
τ_m	Maximum roll stress, N/m^2
τ_R	Specific resistive torque of the roll bearings, Nm/m
τ_t	Torsion stress, N/m^2

Table 1 Modelling of Helwan cold rolling stand for $t = 2$ mm, $\sigma_1 = 10$ and $\sigma_2 = 40$ MN/m^2

Reduction (%)	10	20	30	40	50
Rolling force (MN)	3.29	5.71	8.34	11.21	14.33
Rolling torque (kNm)	3.51	25.85	54.59	89.31	129.6
Forward slip (%)	4.30	5.71	6.65	7.47	8.39
Roll deflection (mm)	0.0146	0.0253	0.037	0.0497	0.0636
Roll stress (MN/m^2)	294.8	511.0	746.7	1003.6	1282.8
Rolling power (kW/rev/min)	4.892	7.859	11.59	16.09	21.41
Efficiency (%)	94.30	89.70	83.99	77.41	70.13

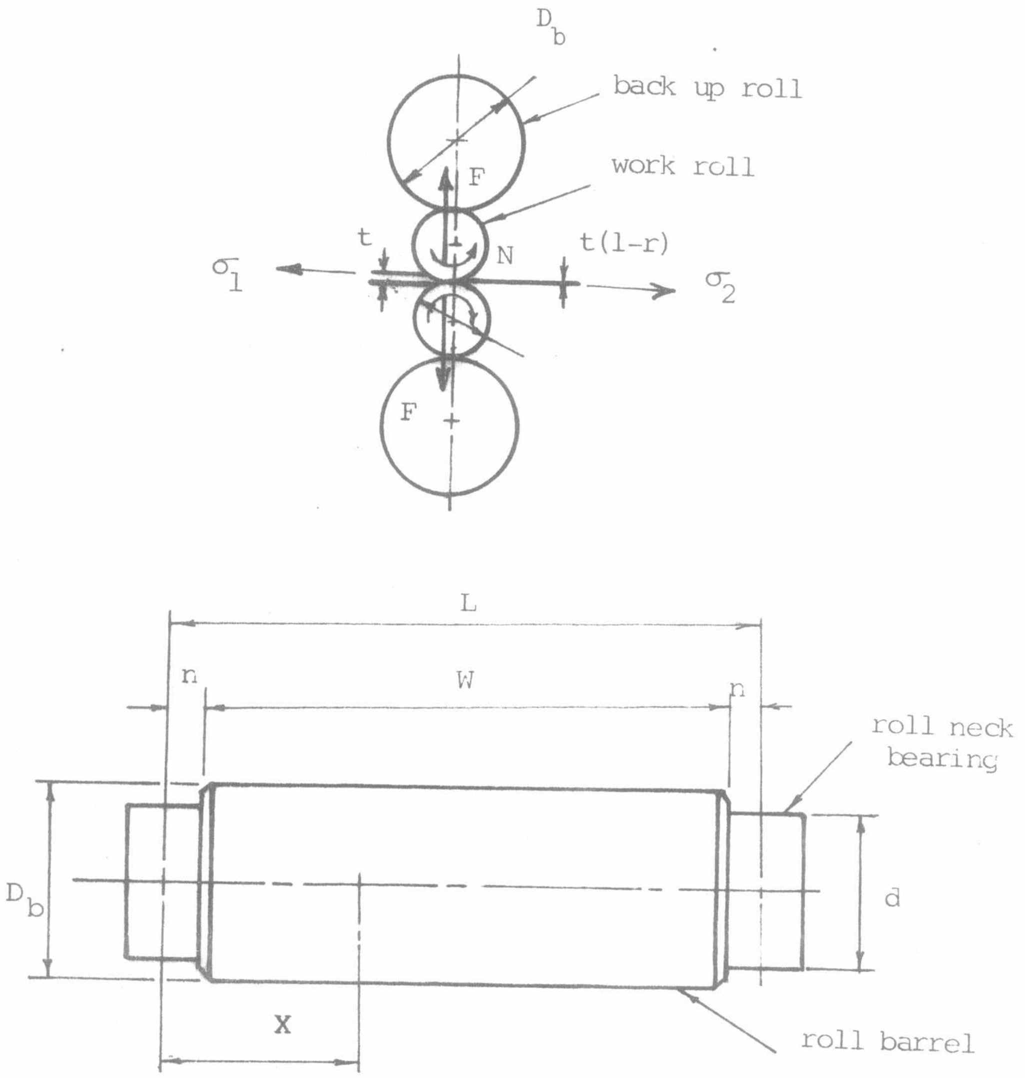

Fig.1 Back up roll dimensions and rolling parameters.