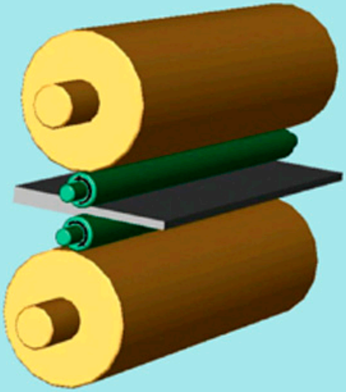
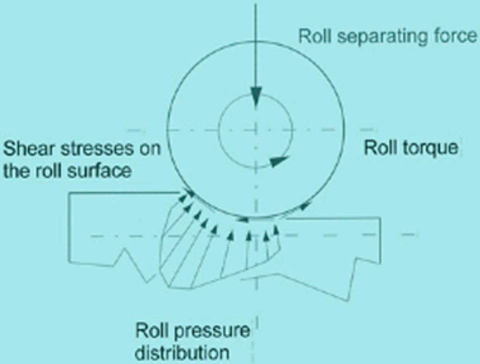
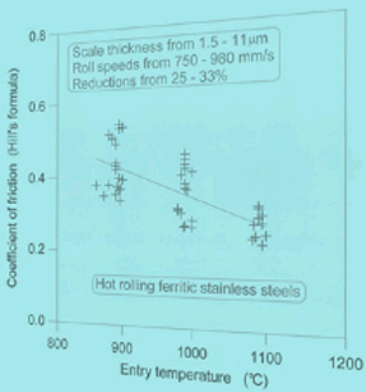
$$\frac{d}{dx}\left[h\left(p - 2k \mp \tau\frac{dy}{dx}\right)\right] = 2\left(p\frac{dy}{dx} \pm \tau\right)$$





Primer on Flat Rolling

A monograph for those who need to understand the basics of the flat rolling process



John G. Lenard

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Primer on Flat Rolling

By

JOHN G. LENARD

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I dedicate this book to my wife, Harriet and my daughter, Patti.
Their active support, encouragement and love made
the writing possible and easy.

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CONTENTS

PREFACE

I have been dealing with problems of the flat rolling process for the last 30 years. This included mathematical modelling, experimentation, consulting, publishing in technical journals, presenting my research at conferences and in industry, as well as lecturing on the topic at levels, appropriate for second and third year undergraduate students, graduate students and practicing engineers and technologists of aluminum and steel companies. The present book is a compilation of my experience, prepared for use by practitioners who work with metal rolling and who want to know about the "why"-s, the "what"-s and the interdependence of the material and process parameters of the rolling process. The book may also be useful for graduate students, researching flat rolling.

My interest in the process began while I spent a year at Stelco Research as an NSERC Senior Industrial Fellow, shortly after starting my academic career. I became aware of the tremendous complexity underlying the seemingly very simple process of metal rolling. I realized that while the process of flat rolling – that of two cylinders rotating in opposite directions and reducing the thickness of a strip as it passes between them – has not changed for centuries, its current sophistication places it at the top of the "high tech" activities. On return to academia, and as soon as research funds allowed, I designed and built a simple two-high experimental rolling mill and instrumented it to measure the important variables. The mill has been in use ever since to roll various metals – mostly aluminum and steel alloys – under a large variety of conditions. These conditions included dry and lubricated passes, use of neat oils and emulsions, high, low and intermediate temperatures, heated and non-heated rolls, speeds and reductions as high and low as the mill allowed. During these experiments, my students and I used smooth and rough roll surfaces, prepared by grinding or sand blasting.

In each of the tests, the roll separating forces, the roll torques, the entry and exit thickness, the rolling speed, the forward slip, the entry and exit temperatures of the strip, the roll's surface temperature, the amount of the lubricant, the flow rate and the temperature of the emulsion, the droplet size in the emulsion, the change of the width and the reduction of the strips were measured.

In addition to the experiments performed by myself, by academic visitors from China, Egypt, Germany, Hungary, India, Israel, Japan, Poland and South Korea, and by my graduate students, twice each year my undergraduate classes, typically 80–100 students strong, performed flat rolling tests, providing me with a very respectable collection of data.

Mathematical modelling of the process proceeded parallel to the experimental studies. The attention was on establishing the predictive abilities of the available models of the flat rolling process. The assumptions made in the derivation of the traditional 1D models were critically examined and were improved on by developing an advanced 1D model which makes use of as few arbitrary assumptions as possible. The use of finite-element models was also explored, in co-operation with Prof. Pietrzyk (University of Mining and Metallurgy, Krakow, Poland) and his colleagues and students.

During my academic career, I offered, once or twice a year, a specialist course on rolling, designed for technologists and engineers who work in the metal rolling industry. The educational level of the audience varied broadly, from those who completed high school to those with doctoral degrees. Each year I found two unchanging phenomena. The first was the shaky background my listeners possessed, essentially regardless of their education. When asked about the difference between engineering strains and true strains, about the difference between the plane-stress and the plane-strain conditions, the difference between static and dynamic recrystallization, and so on, the large majority of them betrayed serious ignorance. The second was the lack of a textbook that includes all I needed to develop the ideas in the course. The present book, resulting from the notes I used in these courses, attempts to compile, present and explain the disparate components, needed for a clear understanding of the topic.

The book contains 11 chapters. The first 10 of these deal with various aspects of the flat rolling process and the 11th presents a set of assignments and incomplete solutions, formulated to test the understanding of the reader of the material presented. Each chapter ends with a set of Conclusions.

The flat rolling process is defined in Chapter 1, the Introduction. The objectives are to give a very brief overview of the process. Details of the hot rolling process, using hot strip mills, are given. Continuous casting is described. The cold rolling process and cold mill configurations are presented next.

A general discussion of the rolling process is presented in Chapter 2. The components of a metal rolling system are defined. Reference is made to the rolling mill, designed by Leonardo da Vinci and the scale-model, built following his drawings. A description of the physical and the metallurgical events during the process is given, including the events as the strip to be rolled is ready to enter the roll gap, as it is partially reduced and as the process becomes one of steady-state. The independent variables of the system – the mill, the rolled metal and their interface – are listed. The minimum value of the coefficient of friction, necessary to commence the rolling process is given. Some of the simplifying assumptions that are usually made in mathematical models of the process of flat rolling are critically discussed: these include the idea of "plane-strain plastic flow" and "homogeneous compression of the strip". Microstructures of a fully recrystallized Nb steel, an AISI 1008 steel and a cold-rolled low carbon steel are presented.

Mathematical modelling of the rolling process is the topic of Chapter 3. Traditional and more advanced models are discussed in terms of their capabilities as far as their predictions are concerned. Models for both mechanical and metallurgical events are included. The chapter ends with the identification of three parameters, necessary for efficient, accurate and consistent modelling: the coefficients of heat transfer and friction and the resistance of the material to deformation.

Chapters 4 and 5 treat these in turn; material behaviour and tribology, respectively. In both, the emphasis is on how the concepts are to be used when combined with the models, presented in the previous chapter.

The objectives in preparing Chapter 6 are somewhat different. The chapter is entitled "Sensitivity studies" and in spite of some examination of the sensitivity of the predictions in previous chapters, some more calculations and applications are added.

Temper rolling is considered in Chapter 7. The differences between the usual flat rolling process and temper rolling are pointed out. Several mathematical models are given and the assumptions made in their development are discussed. The components that should make up a complete model of the process are listed.

The tenor of the book changes at that point. In each of Chapters 8, 9 and 10 – accumulative roll-bonding, cold-roll bonding and flexible rolling , respectively – a review of the literature is followed by the detailed descriptions of experimental work.

Chapter 11 contains two sections. In the first, problems are listed, for each of the chapters. Some of these require the direct application of the expressions and the formulas presented in the book. Some answers require Internet searches. Some require development of computer programs. Some are suggested topics for seminars or class discussions. In the second part, the solutions are given. Again, this is done in a variety of ways: in some cases detailed solutions are given while in some others, only the numerical answers are indicated. As well, in some instances, only a set of hints and recommended approaches are suggested.

I would like to acknowledge the contributions of my undergraduate and graduate students without whom my research would not have progressed. Also, I would like to thank the visiting scientists with whom co-operation was always most enjoyable.

LIST OF SYMBOLS

Ar_1, Ar_3	Austenite to ferrite transformation; stop and start temperatures, respectively
A, A_r	Apparent and true areas of contact, respectively
B	Material constant
C	Material constant, indicating strain-rate hardening; also half the distance between the roll centres in eq. 3.29
$[C]$, C_{eq}	Carbon content, %; carbon equivalent
D	Diameter of the work roll
D_α, D_γ, D_r	Ferrite and austenite grain size; austenite grain size after recrystallization, respectively
D_{DRX}	Austenite grain size after dynamic recrystallization
D_{MD}	Austenite grain size after metadynamic recrystallization
E, E'	Elastic modulus; composite elastic modulus, respectively
F_I	Inertia force
H	Hardness
J^*	Externally supplied power
J_2	Second invariant of the stress deviator tensor
K	Material constant, strength coefficient
K_y	Grain boundary unlocking term
L	The contact length
M	Roll torque for both rolls per unit width
N	Roll rpm
P, P_{total}	Power required for plastic deformation and the total power needed to drive the rolling mill, respectively
P_n	Friction losses in four roll-neck bearings
P_r	The roll separating force per unit width
Q_p	The pressure intensification factor; a multiplier, accounting for the shape factor and the coefficient of friction
Q_{RX}	Activation energy for recrystallization
R', R	The radius of the flattened roll (by Hitchcock's equation) and the original radius of the roll, respectively
S, S_Γ, S_i	Surface; also mill stiffness in eq. 3.94; surfaces in the upper bound theorem, eq. 3.61, respectively
S_{ij}	Components of the stress deviator tensor
S_f, S_b	The forward and the backward slip
T, T_0	Temperature; roll temperature some distance below the surface

$\Delta T_{\text{gain}}, \Delta T_{\text{loss}}$	Temperature rise and loss of the strip in the pass, respectively
$T_{\text{strip}}, T_{\text{roll}}$	Temperature of the strip and the roll, respectively
T_{NRX}	Temperature above which recrystallization will occur
V	Volume
$\dot{W}$	The flattening rate
X, X_{DRX}	The recrystallized volume fraction; dynamically recrystallized volume fraction, respectively
X_{MD}	Metadynamically recrystallized volume fraction
Y	Material constant
Z	Zener-Hollomon parameter
a	Acceleration
a, b	Constants
c_{p}	Specific heat of the rolled strip
d	Diameter of the roll-neck bearing
$f_{\text{t}}, f_{\text{n}}$	Friction force, and the normal force, respectively
h	The thickness of the strip
h_{entry}	The thickness of the strip at the entry
h_{exit}	The thickness of the strip at the exit
h_{ave}	The average of the entry and the exit thickness
h_{min}	The minimum rollable thickness
h_{np}	The thickness of the strip at the neutral point
$h_{\text{film,ave}}, h_{\text{s}}$	Average oil film thickness; smooth oil film thickness
k	Yield strength of the material in pure shear
l_{a}	The lever arm
m, m_{ave}	Strain rate hardening exponent; also mass; average friction factor, respectively
n, n_1	Strain hardening exponent
p, p_{ave}	Roll pressure; average roll pressure
p, q, r, s	Material constants
p_{s}	Shakedown pressure
r	Reduction
t	time
v	Speed of the rolled strip; also Poisson's ratio in equation 3.5
v_{r}	Roll surface speed
w	Width of the strip
x	Distance along the direction of rolling, measured from the line connecting the roll centres
x_{n}	Location of the neutral point
$\alpha, \overline{\alpha}$	Heat transfer coefficient; parameter in Hatta's equation
β^*	Correlation distance
γ	Austenite
δ_{ij}	Kronecker's delta
$\varepsilon_{0.5\text{X}}$	Strain for 50% recrystallization