

Thermal Analysis of Lubricating Film Formation in Inlet Zone in Cold Rolling of Metallic Strips

by

Prahlad Singh
Applied Mechanics Department

Submitted

In fulfillment of the requirements of the degree

of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

July-2011

Certificate

This is to certify that the thesis titled “**Thermal Analysis of Lubricating Film Formation in Inlet Zone in Cold Rolling of Metallic Strips**” being submitted by **Mr. Prahlad Singh** (2004AMZ8001) to the **Indian Institute of Technology Delhi**, New Delhi, India, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our guidance and fulfilled the requirements for the submission of this thesis. As per our awareness the results contained in this thesis have not been submitted in part or in full to any other university or institute for award of any degree or diploma.

We also certify that Mr. Prahlad Singh has pursued the prescribed course of research at Indian Institute of Technology Delhi as a part time student.



Prof. Y. Nath
(Supervisor)
Professor and Head
Applied Mechanics Department
Indian Institute of Technology
Delhi New Delhi – 110 016, India



Dr. R. K. Pandey
(Supervisor)
Associate Professor
Department of Mechanical Engineering
Indian Institute of Technology Delhi
New Delhi – 110 016, India

Date: 26th July 2011
Place: IIT Delhi, New Delhi

Acknowledgements

I wish to express my deep sense of gratitude and indebtedness to my thesis supervisors, **Prof. Y. Nath** and **Dr. R. K. Pandey**, for their constant support, inspiration and encouragement during the course of this research work. Their comments and suggestions at various stages have immensely improved my understanding of the subject and paved the way in the solutions of the governing equations reported in this thesis. I am fortunate to have worked under their guidance that instilled research ability in me.

I acknowledge all the supports provided by **Prof. K. S. Shishodiya** (formerly Head, Applied Mechanics Department), **Prof. P. K. Sen** (formerly Head, Applied Mechanics Department), and **Prof. Y. Nath** (Head, Applied Mechanics Department), in completion of this thesis. I am highly thankful to **Prof. D. Ravi Kumar** (external expert in SRC), Department of Mechanical Engineering, Indian Institute of Technology Delhi, for his valuable suggestions and vital feedbacks during various presentations. I express my sincere gratitude to internal SRC members **Prof. D. K. Sehgal**, **Prof. Suhail Ahmed**, and **Prof. S. V. Veeravalli**, for their kind technical suggestions and help during the presentations throughout this endeavor. I would also like to acknowledge the timely help provided by some other faculty members of Applied Mechanics Department, IIT Delhi. I must thank the staff members of Applied Mechanics Department, IIT Delhi for their official help in processing the papers.

My sincere thanks also go to **Prof. B. C. Nakra** (Pro-Vice chancellor, ITM University, Gurgaon, Haryana, India) for enlightening me in pursuing the research. I pay my sincere thanks to **Prof. O. P. Chawla** (Professor, ITM University, Gurgaon, Haryana, India) for encouraging me at the time of pressure during pursuing this endeavor.

I am highly grateful to the hon'ble members of the governing body (ITM University, Gurgaon, Haryana, India) **Mr. Avdhesh Mishra**, **Mr. S. S. Mehra** and **Mr. V Daulat Singh** for encouraging me during this endeavor.

I would like to make special mention of my co-researchers at IIT Delhi, **Dr. Rajesh Kumar Sharma** and **Mr. Bhavesh Kachhia** for their supports and motivations during early days of this endeavor. I gratefully thank my colleague **Mr. Ashwini Sharma** and **Mr. S. Parmeshwar** at ITM University Gurgaon for their day-to-day supports and encouragement.

Last but not the least; I would like to thank my parents for giving birth to me and supporting me spiritually throughout my life. Finally, I express my deep gratitude and love to my wife Anita for her care and never-ending support in my work. I express my love to my daughter Aadhika who brings happiness and harmony in my life.



(PRAHLAD SINGH)

Date: 26th July 2011

Place: IIT Delhi

Abstract

In cold rolling process, the energy for the deformation of the strip is transmitted by the rolls through the interfacial friction force. The presence of an effective lubricant film thickness between contact surfaces in the cold strip rolling operation increases the forming limit, reduces the roll wear, and improves the surface quality of the products. Existence of too thick lubricating film produces matt surface due to insufficient constraint by the rolls, while too thin lubricating film might allow direct metal-to-metal contact leading to rapid roll wear, strip surface scoring and other defects. Therefore, a better understanding of the lubrication mechanism in terms of operating parameters for maintaining an optimum lubricating film thickness at the strip-roll interface can promote efficient production with better surface quality of the strips. Formations of hydrodynamic lubricating film at the rolls-strip interfaces mainly take place in the inlet zone, while the work zone governs the friction force and pressure engendered in effecting the deformation. One of the mechanisms still to be simulated relatively in depth in the lubrication of cold strip rolling is the starvation where the amount of available lubricant happens to be insufficient to completely fill the inlet zone. Starvation generally occurs due to excessive roll speed and high lubricant's viscosity, or due to the limited supply of lubricant. Under starved conditions, the minimum film thickness goes down much below than the one exists with the fully flooded condition. It is worth mentioning here that design methodologies for the lubricated strip-roll interfaces developed over the years are primarily under the assumption of fully flooded conditions. Even the advance design procedures of the lubricated interface in cold strip rolling are mainly based on isothermal hydrodynamic lubrication models which do not incorporate the role of viscous shear heating in the lubricant. Hence, it is vital task to study the performance characteristics (mainly minimum film thickness) of the lubricated inlet

zone of roll-strip interface by incorporating the combined effects of starvation and viscous shear heating of the lubricant considering smooth and rough contacts. An effort has been done in this thesis to address the above concerns.

The primary objective of this thesis is to do thermohydrodynamic lubrication analysis of fully flooded and starved smooth and rough inlet zones in cold rolling process for the development of empirical relations for predictions of isothermal and thermal minimum film thickness and maximum film temperature rise. However, the limited objective of the thesis is to correlate the results obtained by applying minimum film thickness relations (developed based on the lubricating oil) with the minimum film thickness results achieved by the prior researchers using emulsions. Numerical studies have been done for the fully flooded and starved thermohydrodynamic lubrication (THL) of inlet zones of rolls-strip interfaces operating at range of material parameter ($G = 5$ to 11), reduction ratio ($R_D = 0.05$ to 0.15), slip (S goes up to 0.20), starvation distance ($|X_{starved}| = 1.25$ to 10), surface roughness ($\sigma = 0.75$ to $2.2.5 \mu\text{m}$), and thermal loading parameter ($Q = 3$ to 340). In order to have reasonable accuracy in numerical results with less computational cost, the Lobatto quadrature technique as developed by Elrod and Brewe [75] has been used for mathematical modeling and evaluation of interface performance parameters for smooth interface. However, thermal model proposed by Chang and Farnum [77] has been employed for rough lubricated interface. Results computed based on the proposed models are validated against the experimental and theoretical results available in the open literature. Significant reductions in minimum film thickness and maximum film temperature are obtained with respect to fully flooded conditions in presence of starvation. Based on the results embodied in this thesis, empirical relations have been developed for the prediction of dimensionless isothermal and thermal minimum

film thickness and dimensionless maximum film temperature rise for fully flooded as well as for the starved conditions. It is believed that empirical relations proposed in this thesis may be of worth to design and maintenance engineers of cold rolling industries.

Contents

Certificate	i
Acknowledgements	ii
Abstract	iv
Contents	vii
List of Figures	xi
List of Tables	xxiv
Nomenclature	xxvi

Chapter-1 Introduction

1.1 Overview	1
1.2 Lubricating film formation at the interface of roll-strip	5
1.3 Scope of research and importance of inlet zone investigations	7
1.4 Outline of thesis	8

Chapter-2 Literature Review

2.1 Numerical investigations	11
2.1.1 Use of neat lubricating oil in the analysis	11
2.1.1.1 Isothermal analysis of smooth and rough interfaces	12
2.1.1.2 Thermal analyses of smooth and rough interfaces	21
2.1.2 Use of emulsion in the analysis	25
2.1.2.1 Isothermal analysis of smooth and rough interfaces	25
2.1.2.2 Thermal analysis of smooth and rough interfaces	28
2.2 Experimental studies	29
2.2.1 Use of neat lubricating oil in experiment	29

2.2.2	Use of emulsion in experiment	36
2.3	Conclusions of literature review	44
2.4	Importance of lubrication investigation in inlet zone	45
2.4	Objectives of present studies	46
 Chapter-3 Mathematical Models and Computational Techniques		
3.1	Thermohydrodynamic analysis of smooth inlet zone	47
3.1.1	Lobatto quadrature technique	47
3.1.2	Film thickness relation	52
3.1.3	Generalized Reynolds equation	52
3.1.4	Energy equation	54
3.1.5	Rheological relation for lubricant	56
3.1.6	Computational technique	57
3.2	Thermohydrodynamic analysis of rough inlet zone	62
3.2.1	Average Reynolds equation	63
3.2.2	Energy equation	65
3.2.3	Computational technique	68
3.3	Definition of dimensionless parameter	70
 Chapter-4 Fully Flooded and Starved Lubrication Studies of Smooth Inlet Zone		
4.1	Introduction	73
4.2	Governing equations	74
4.3	Computational methodology	76
4.4	Validation of proposed model	76
4.5	Results and discussion	78
4.5.1	Film pressure variation	79

4.5.2	Film temperature rise variation along rolling direction	85
4.5.3	Film temperature rise variation across the lubricating film	94
4.5.4	Film thickness variation in fully flooded and starved cases	103
4.5.5	Variation of thermal correction factor	114
4.6	Concluding remarks	122
Chapter-5 Fully Flooded and Starved Lubrication Studies of Rough Inlet Zone		
5.1	Introduction	123
5.2	Governing equations	124
5.3	Computational methodology	128
5.4	Validation of proposed model	128
5.5	Results and discussions	130
5.5.1	Film pressure variation	131
5.5.2	Film temperature rise variation along rolling direction	142
5.5.3	Film temperature rise variation across the lubricating film	161
5.5.4	Film thickness variation in fully flooded and starved cases	181
5.5.5	Variation of thermal correction factor	194
5.6	Concluding remarks	206
Chapter-6 Empirical Relations and Application		
6.1	Empirical relations for minimum film thickness and maximum film temperature rise	207
6.2	Application of film thickness relations for the emulsion lubricated cold rolling processes	212
6.3	Concluding remarks	215
Chapter-7 Conclusions and Scope for Future Studies		
7.1	Conclusions	216

7.2 Scope for future studies	219
References	220
Appendix-A	228
Appendix-B	230
Appendix-C	233
Appendix-D	236
Appendix-E	241