Analytical and Experimental Study on Asymmetrical Sheet Rolling

ANALYSIS OF FORMING, JOINING, and Casing

ME-548

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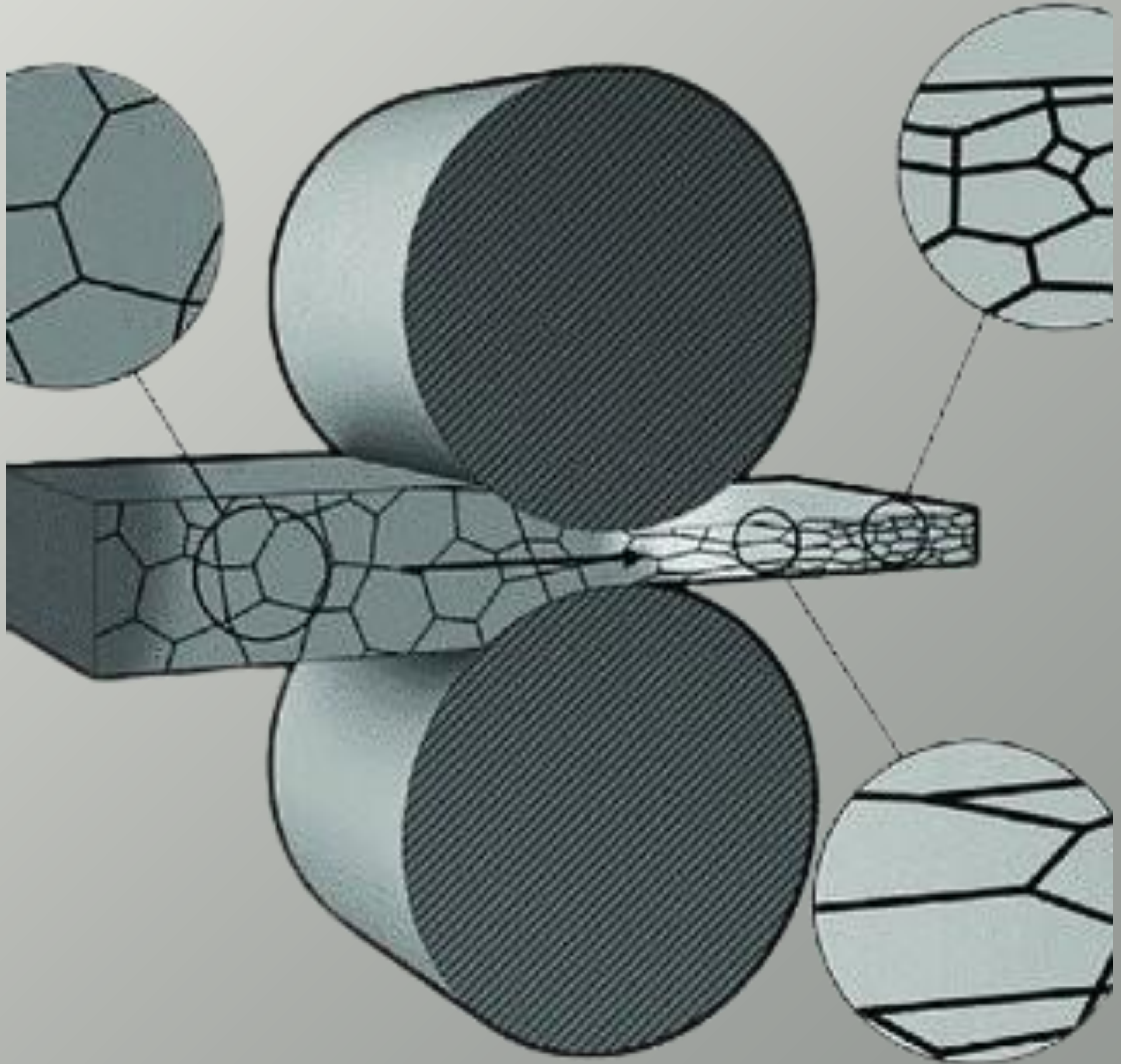

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CONTENT

INTRODUCTION

Asymmetrical sheet rolling processes, for which the peripheral velocity or radius of the upper roll may be different from those of the lower roll, have become more and more important, in light of the fact that it can gain such advantages as lower rolling pressure distribution, resulting in less rolling force and less torque.

Benefits for the reduced rolling force:

- improved properties of the sheet surfaces can be obtained;
- shape and thickness can be easily controlled;
- reduction can be increased and the number of rolling pass can be decreased;
- rolling process for the high tensile strength steel and extremely thin strip can be possible;
- energy can be saved by the decrease of anneal treatment; etc

Research on Asymmetrical Rolling:

- Most studies have been experimental, such as Yamamoto et al.'s cold sheet rolling experiments and Ghobrial's contact stress study using photoelastic methods.
- Some numerical models use the slab method, Runge-Kutta, upper bound method, or finite element method, but these are often time-consuming and complex for online use.

Existing models are inadequate for predicting rolling force and torque in real-time. Therefore, analytical approaches are necessary for the industry. The authors propose an analytical model based on the slab method for both cold and hot sheet rolling with constant shear friction, providing quick and reliable rolling pressure distributions, forces, and torques.

NOTATION

- L
- P
- T
- p
- q
- X
- h
- K
- σ_{yp}
- r
- q_i
- q_0
- h_0
- h_i
- n
- R_1, R_2
- T_1, T_2
- m_1, m_2
- θ_1, θ_2
- V_1,V_2
- p_1,p_2
- F_{sl},F_{s2}
- τ_1, τ_2

the length of contact

rolling force per unit width

total calculated rolling torque per unit width

vertical stress at the roll gap

horizontal stress at the roll gap

horizontal distance from exit point of roll gap

variable sheet thickness

mean material yield strength in shear

mean yield strength

reduction

back tension at the entrance

front tension at the exit

final sheet thickness

initial sheet thickness

strain-hardening expo

radius of the upper and lower rolls, respectively

rolling torque of the upper and lower rolls, respectively

friction factor of the upper and lower rolls, respectively

MATHEMATICAL MODEL

ASSUMPTIONS:

1. The roll is a rigid body, and the sheet being rolled is a rigid-plastic material.
2. The plastic deformation is in plane strain.
3. Stresses are uniformly distributed within elements. The vertical stress (p) and horizontal stress (q) are regarded as principal stresses .
4. The condition of constant shear friction persists throughout the arc of contact, i.e. τ= mk. As simulating hot rolling, friction stress τ is equal to the mean shear yield strength k, namely m = 1, for cold rolling m should less very small.
5. The flow directions of the sheet at the entrance and exit of the roll gap are both horizontal.
6. The total roll contact arc is comparatively smaller than the circumference of the roll.

MATHEMATICAL MODEL

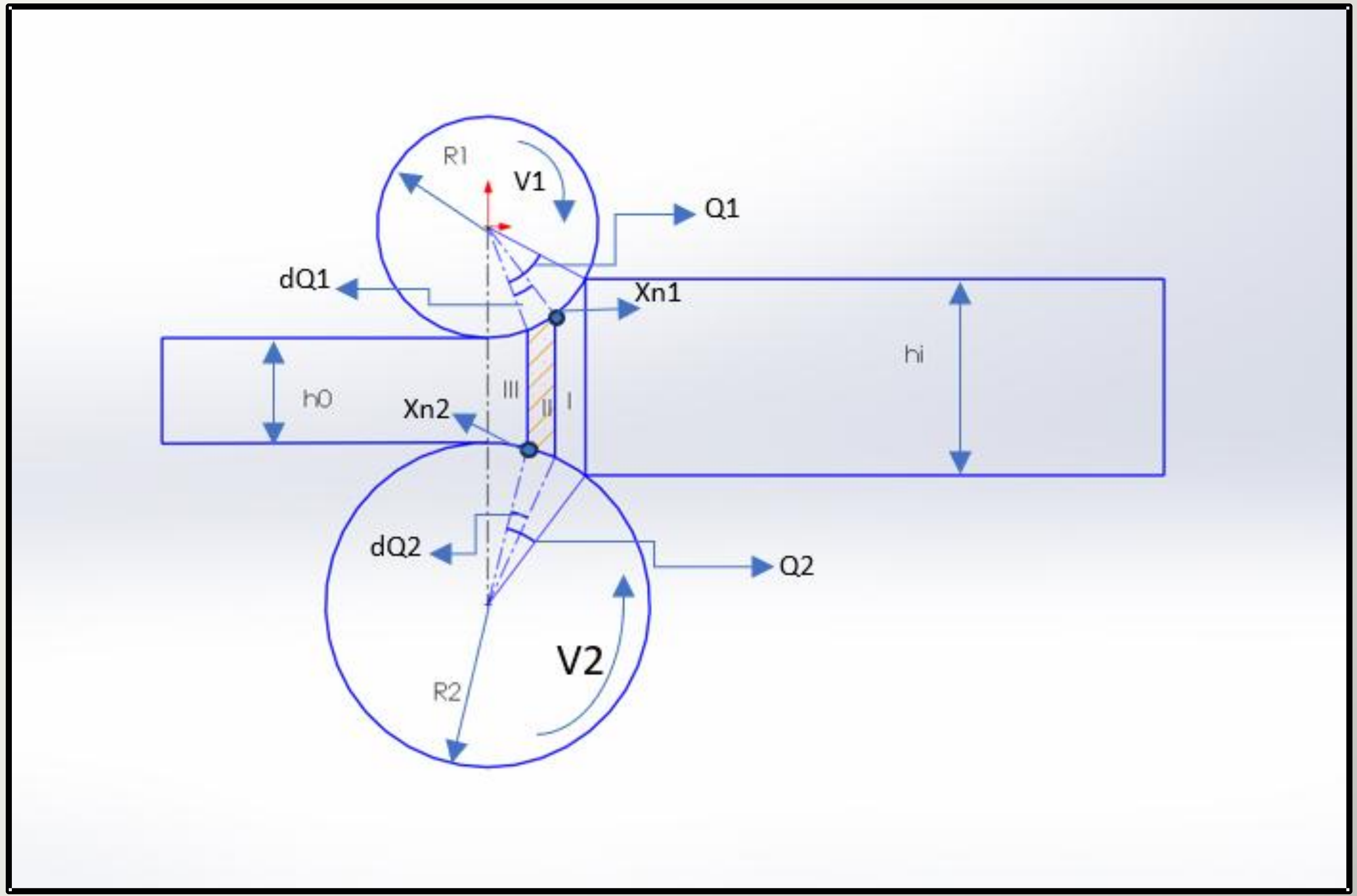


Fig. 1. Schematic illustration of the mathematical model.

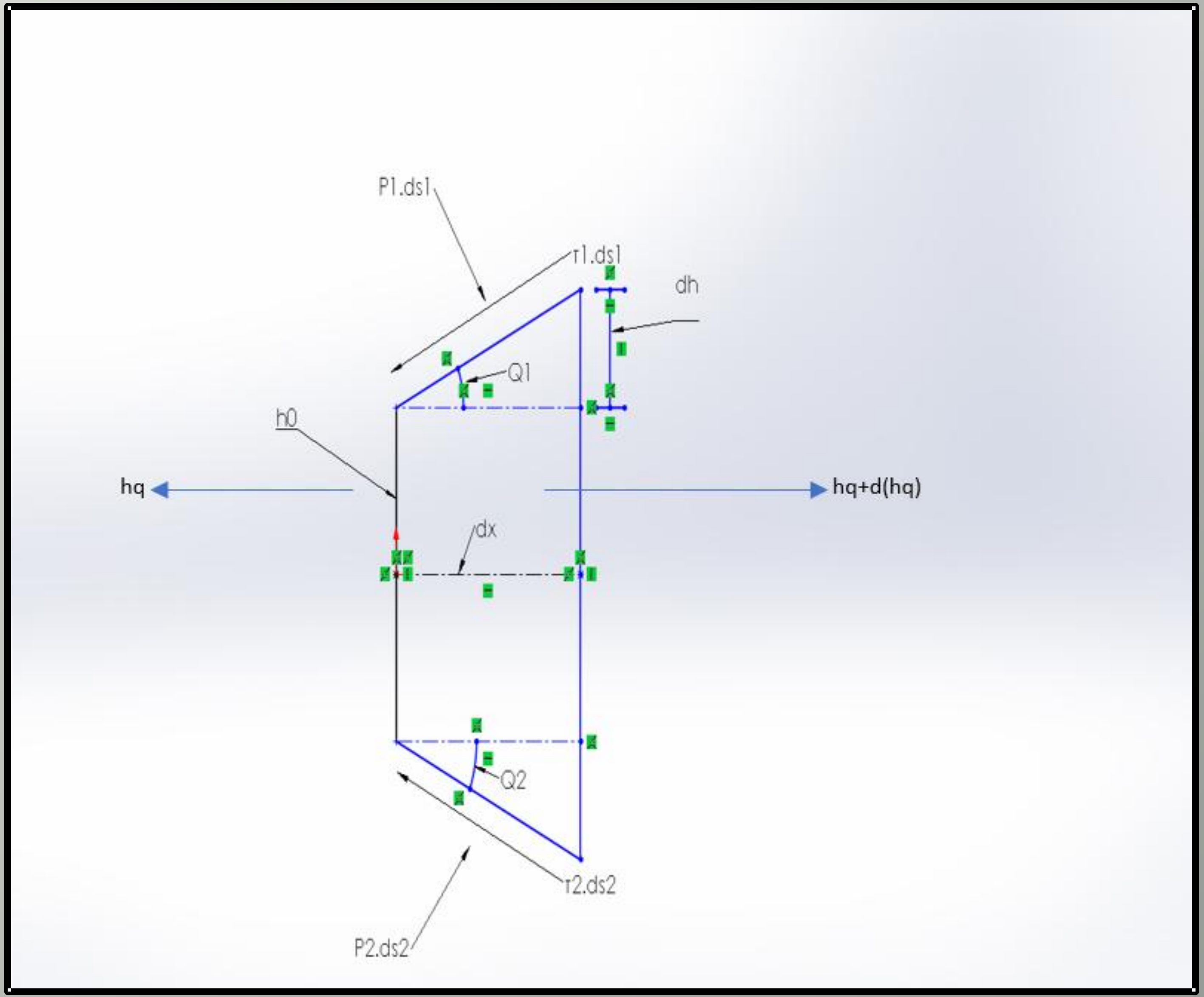


Fig. 2. Material element in region I.

MATHEMATICAL MODEL CONTINUED......

The mathematical expressions for the horizontal and vertical force equilibriums are summarized as

$$\frac{d(hq)}{dx} + p_1 \tan\theta_1 + p_2 \tan\theta_2 - (\tau_1 + \tau_2) = 0$$

$$p = p_1 + \tau_1 \tan\theta_1 = p_2 + \tau_2 \tan\theta_2 \ .$$

$$h\frac{dq}{dx} + (p + q)\frac{dh}{dx} = \tau_1 \frac{x^2}{R_1^2} + \tau_2 \frac{x^2}{R_2^2} + \tau_e$$

$$h = h_0 + \frac{x^2}{R_{eq}}, \quad \frac{dh}{dx} = \frac{2x}{R_{eq}}, \quad R_{eq} = \frac{2R_1R_2}{R_1 + R_2}, \quad \tau_e = \tau_1 + \tau_2$$

After applying plane strain condition and von-misses criterion

τ_e is the effective friction stress, and Req is the so-called effective radius. The yield criterion of the sheet for plane strain can be expressed as

$$p + q = 2k$$

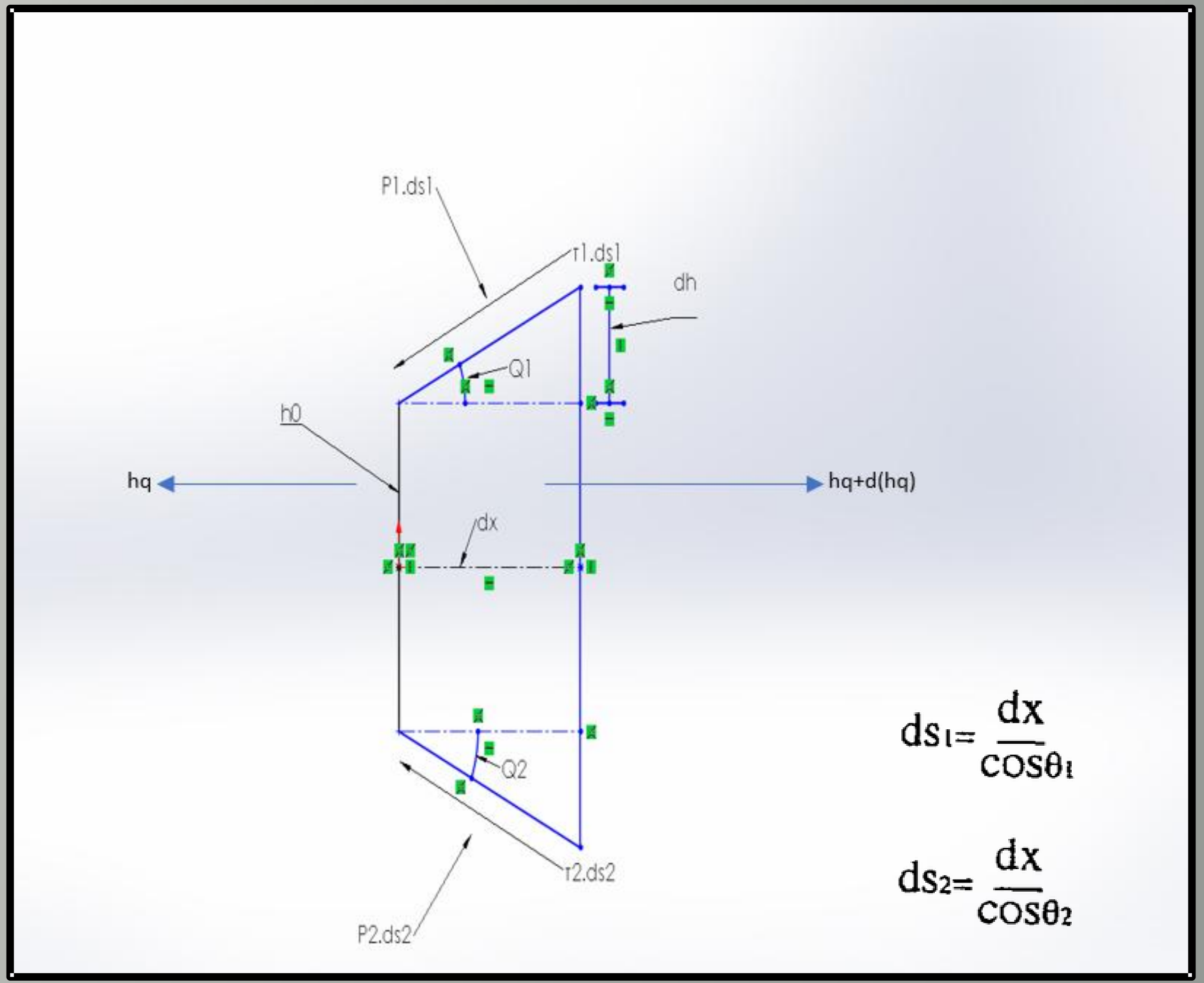


Fig. 2. Material element in region I.

$$p = -Ax + 2k\ln(x^2 + R_{eq}h_0) + \frac{E}{\sqrt{R_{eq}h_0}}\omega + c^*$$

$$A = R_{eq}\left(\frac{\tau_1}{R_1^2} + \frac{\tau_2}{R_2^2}\right), \quad \omega = \tan^{-1}\frac{x}{\sqrt{R_{eq}h_0}}, \quad E = R_{eq}h_0A - R_{eq}\tau_e .$$

Shear Friction Stress Direction

In-zone-I:

The directions of the friction force are all forward, i.e. The sheet velocity is slower than those of the upper and lower rolls, accordingly the effective friction stress

τ_e is $m_1k + m_2k.$

In-zone-II:

The friction forces are in reversed direction, thus for the case of V2 > V1,

$$\tau_e = -m_1k + m_2k = (m_2 - m_1)k$$

In-zone-III:

The form of the differential equation in zone iii is the same as that in zone i, except that the effective friction stress because the directions of the friction forces are backward, so the effective friction stresses is

$$\tau_e = -m_1k - m_2k = -(m_1 + m_2)k,$$

BOUNDARY CONDITIONS:

The velocity of the lower roll is assumed to be quicker than that of the upper roll. The neutral point of the upper roll is denoted by Xn1, and that of the lower roll by Xn2t. The boundary conditions for those three distinct regions can be expressed as follows:

(i) *Zone III* $(0 \leqslant x \leqslant x_{n2})$, $\tau_{e3} = -(m_1 + m_2)k$

At $x = 0$ [or $\omega = 0$]

$$c_3^* = 2k[1 - \ln(R_{eq} h_0)] - q_0$$

$$p_{III} = -A_3 x + 2k \ln(x^2 + R_{eq} h_0) + \frac{E_3}{\sqrt{R_{eq} h_0}} \omega + c_3^*$$

$$A_3 = -R_{eq} k\left(\frac{m_1}{R_1^2} + \frac{m_2}{R_2^2}\right), \quad E_3 = R_{eq} h_0 A_3 - R_{eq} \tau_{e3} .$$

(ii) *Zone I* $(x_{n1} \leqslant x \leqslant L)$, $\tau_{e1} = (m_1 + m_2)k$.

At $x = L$[or $\omega = \omega_i = \tan^{-1}(L/\sqrt{R_{eq} h_0})$]

$$c_1^* = 2k - q_i + A_1 L - 2k \ln(L^2 + R_{eq} h_0) - \frac{E_1}{\sqrt{R_{eq} h_0}} \omega_i$$

$$A_1 = R_{eq} k\left(\frac{m_1}{R_1^2} + \frac{m_2}{R_2^2}\right), \quad E_1 = R_{eq} h_o A_1 - R_{eq} \tau_{e1}, \quad L = \sqrt{R_{eq} h_i r} .$$

$$p_I = -A_1 x + 2k \ln(x^2 + R_{eq} h_0) + \frac{E_1}{\sqrt{R_{eq} h_0}} \omega + c_1^*$$

(iii) *Zone II*$(x_{n2} \leqslant x \leqslant x_{n1})$, $\tau_{e2} = (m_2 - m_1)k$

$$-A_3 x_{n2} + 2k \ln(x_{n2}^2 + R_{eq} h_0) + \frac{E_3}{\sqrt{R_{eq} h_0}} \omega_{n2} + c_3^* = -A_2 x_{n2} + 2k \ln(x_{n2}^2 + R_{eq} h_0)$$

$$+ \frac{E_2}{\sqrt{R_{eq} h_0}} \omega_{n2} + c_2^*$$

$$A_2 = -R_{eq} k \left(\frac{m_1}{R_1^2} - \frac{m_2}{R_2^2} \right), \quad E_2 = R_{eq} h_0 A_2 - R_{eq} \tau_{e2}.$$

$$-A_1 x_{n1} + 2k \ln(x_{n1}^2 + R_{eq} h_0) + \frac{E_1}{\sqrt{R_{eq} h_0}} \omega_{n1} + c_1^* = -A_2 x_{n1} + 2k \ln(x_{n1}^2 + R_{eq} h_0)$$

$$+ \frac{E_2}{\sqrt{R^{eq} h_0}} \omega_{n1} + c_2^*$$

$$\omega_{n1} = \tan^{-1} \frac{x_{n1}}{\sqrt{R_{eq} h_0}}, \quad \omega_{n2} = \tan^{-1} \frac{x_{n2}}{\sqrt{R_{eq} h_0}}.$$

$$c_2^* = (A_2 - A_3)\, x_{n2} + F^* \omega_{n2} + c_3^*$$

$$F^* = (E_3 - E_2)/\sqrt{R_{eq} h_0}$$

$$c_2^* = (A_2 - A_1)\, x_{n1} + E^* \omega_{n1} + c_1^*$$

$$E^* = (E_1 - E_2)/\sqrt{R_{eq} h_0}.$$

$$\boxed{(A_2 - A_1)\, x_{n1} + E^* \omega_{n1} + c_1^* - (A_2 - A_3)\, x_{n2} - F^* \omega_{n2} - c_3^* = 0.}$$

$$x_{n1} = \sqrt{V_A x_{n2}^2 + (V_A - 1)\,\frac{h_0}{R_A}}$$

$$V_A = \frac{V_2}{V_1}, \quad R_A = \frac{1}{R_{eq}} - \frac{h_0}{2R_{eq}^2}.$$

$$p_{II} = -A_2 x + 2k\ln(x^2 + R_{eq}h_0) + \frac{E_2}{\sqrt{R_{eq}h_0}}\,\omega + c_2^*.$$

Rolling force:

Once the mean shear yield strength of the material and friction factor between the rolls and sheet are known, the rolling force can be found by integrating the normal rolling pressure over the arc length of contact. Thus the rolling force per unit width is given as

$$P_{III} = \int_0^{x_{n2}} p_{III}\,\mathrm{d}x = III_1^* + III_2^*$$

$$III_1^* = -\frac{A_3}{2}x_{n2}^2 + 2kx_{n2}\ln(x_{n2}^2 + R_{eq}h_0) + (c_3^* - 4k)x_{n2}$$

$$III_2^* = E_3\left(\frac{\omega_{n2}^2}{2} + \frac{\omega_{n2}^4}{4}\right) + 4k\sqrt{R_{eq}h_0}\,\omega_{n2}$$

$$P_{II} = \int_{x_{n2}}^{x_{n1}} p_{II}\,\mathrm{d}x = II_1^* + II_2^*$$

$$II_1^* = -\frac{A_2}{2}x_{n1}^2 + 2kx_{n1}\ln(x_{n1}^2 + R_{eq}h_0)$$
$$+ (c_2^* - 4k)x_{n1} + 4k\sqrt{R_{eq}h_0}\,\omega_{n1} + E_2\left(\frac{\omega_{n1}^2}{2} + \frac{\omega_{n1}^4}{4}\right)$$

$$II_2^* = \frac{A_2}{2}x_{n2}^2 - 2kx_{n2}\ln(x_{n2}^2 + R_{eq}h_0)$$
$$-(c_2^* - 4k)\,x_{n2} - 4k\sqrt{R_{eq}h_0}\,\omega_{n2} - E_2\left(\frac{\omega_{n2}^2}{2} + \frac{\omega_{n2}^4}{4}\right)$$

$$P_I = \int_{x_{n1}}^{L} p_I\,\mathrm{d}x = I_1^* + I_2^*$$

$$P_I = \int_{x_{n1}}^{L} p_I\,\mathrm{d}x = I_1^* + I_2^*$$

$$I_1^* = -\frac{A_1}{2}L^2 + 2kL\ln(L^2 + R_{eq}h_0) + (c_1^* - 4k)\,L$$
$$+ 4k\sqrt{R_{eq}h_0}\,\omega_i + E_1\left(\frac{\omega_i^2}{2} + \frac{\omega_i^4}{4}\right)$$

$$I_2^* = \frac{A_1}{2}x_{n1}^2 - 2kx_{n1}\ln(x_{n1}^2 + R_{eq}h_0) - (c_1^* - 4k)\,x_{n1}$$
$$-4k\sqrt{R_{eq}h_0}\,\omega_{n1} - E_1\left(\frac{\omega_{n1}^2}{2} + \frac{\omega_{n1}^4}{4}\right).$$

$$P = P_{III} + P_{II} + P_I$$

Rolling torque:

The rolling torques, T1 and T2, exerted by the sheet on the upper and lower rolls, respectively, can be calculated by integrating the moment of the shear friction force along the arc length of contact around the roll axis. Therefore

$$T_1 = R_1\left(-\int_0^{x_{n2}} m_1 k\,\mathrm{d}x - \int_{x_{n2}}^{x_{n1}} m_1 k\,\mathrm{d}x + \int_{x_{n1}}^{L} m_1 k\,\mathrm{d}x\right) = R_1 m_1 k(L - 2x_{n1})$$

$$T_2 = R_2\left(-\int_0^{x_{n2}} m_2 k\,\mathrm{d}x + \int_{x_{n2}}^{x_{n1}} m_2 k\,\mathrm{d}x + \int_{x_{n1}}^{L} m_2 k\,\mathrm{d}x\right) = R_2 m_2 k(L - 2x_{n2})$$

and the total torque required is

$$T = T_1 + T_2.$$

RESULTS AND DISCUSSION :

Figure 3: Specific Rolling Pressure for Various Friction Factors (m)

Increase in Rolling Pressure: As the friction factor m increases, the specific rolling pressure distribution along the contact length also increases.

Cross-Shear Region Narrowing: Higher friction factors lead to a slight narrowing of the cross-shear region, impacting the overall deformation pattern.

Neutral Point Shifts: The neutral point on the upper roll (xn1) moves further away from the roll exit, while the neutral point on the lower roll (xn2) shifts closer to the roll entrance.

Implications for Roll Control: Adjusting the friction factor affects the rolling pressure distribution and neutral points, allowing for better control over the deformation during the asymmetrical rolling process.

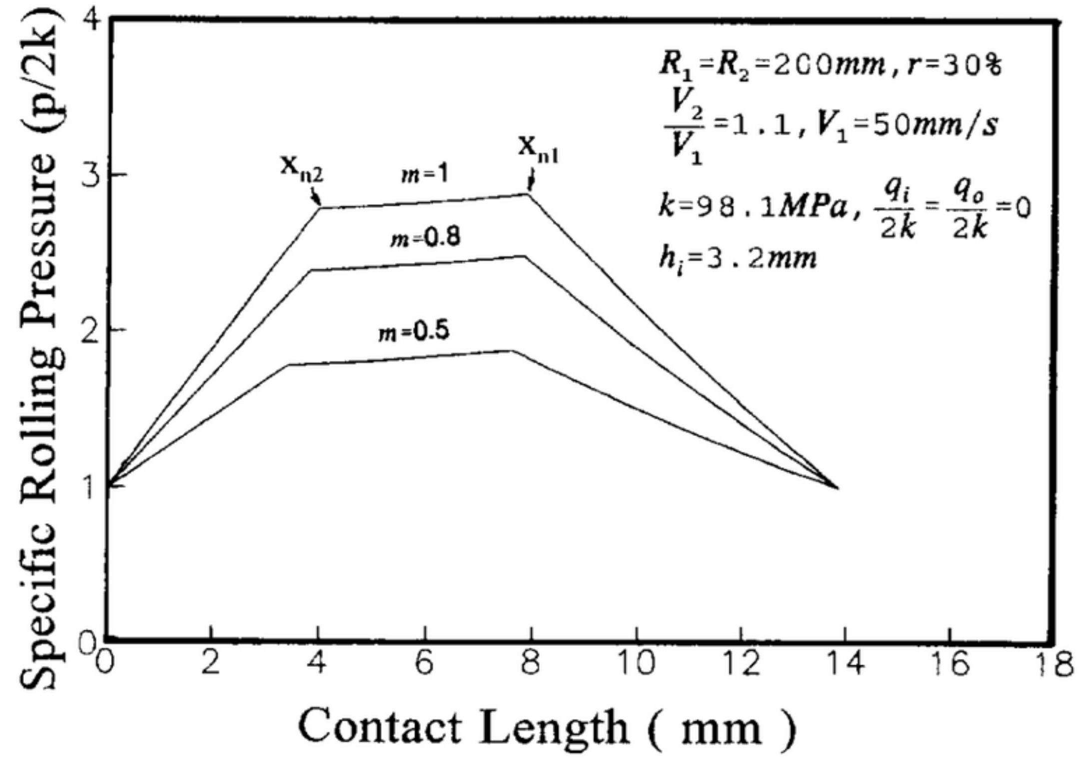


Fig. 3. The specific rolling pressure distributions for various friction factors.

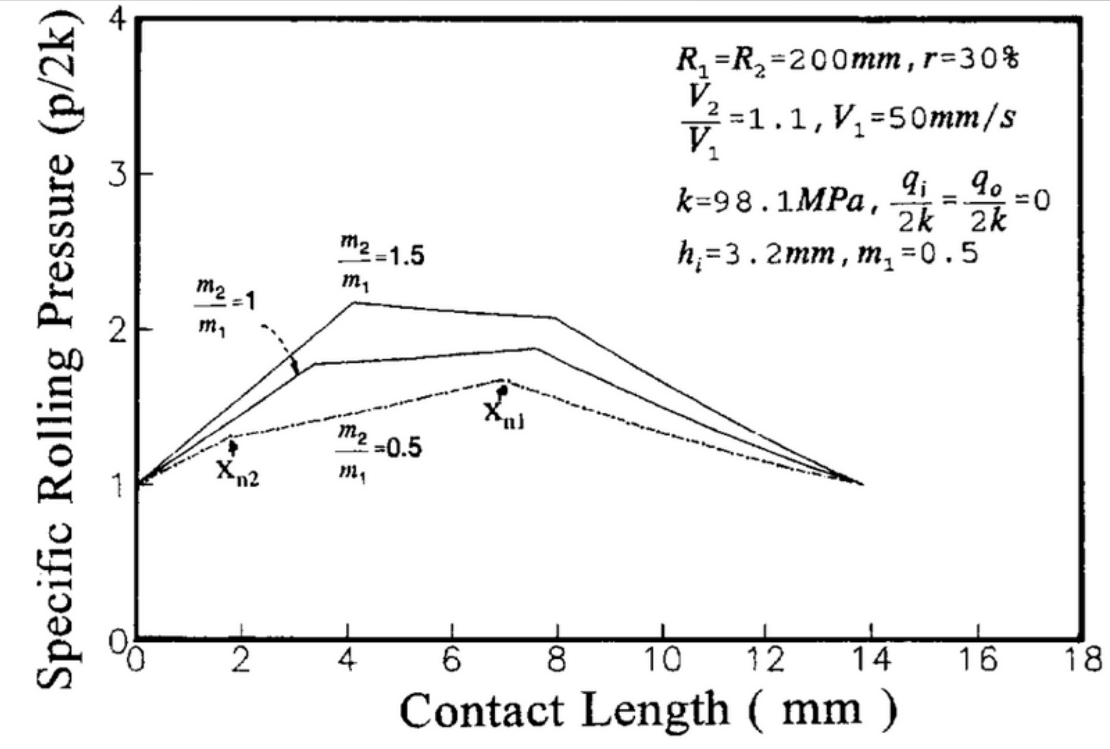
Figure 4: Specific Rolling Pressure for Various Friction Factor Ratios (1m2/m1)

Increase in Rolling Pressure with m2/m1: As the ratio m2/m1 (where m1 is fixed) increases, the overall rolling pressure distribution rises, suggesting a greater force is required.

Shift of Neutral Points Toward Roll Entrance: The neutral points move toward the entrance of the roll gap as the ratio m2/m1 increases, influencing the material flow and pressure distribution.

Difference in Neutral Point Pressure: For m2/m1=0.5, the rolling pressure at the neutral point of the lower roll (xn2) is lower than at the upper roll (xn1). Conversely, when m2/m1=1.5, the rolling pressure at xn2 surpasses that at xn1.

Control of Rolling Pressure Distribution: Adjusting the friction factor ratio m2/m1 offers an effective way to modulate rolling pressure and neutral point positions, which can optimize the rolling process for desired material properties and thickness control.



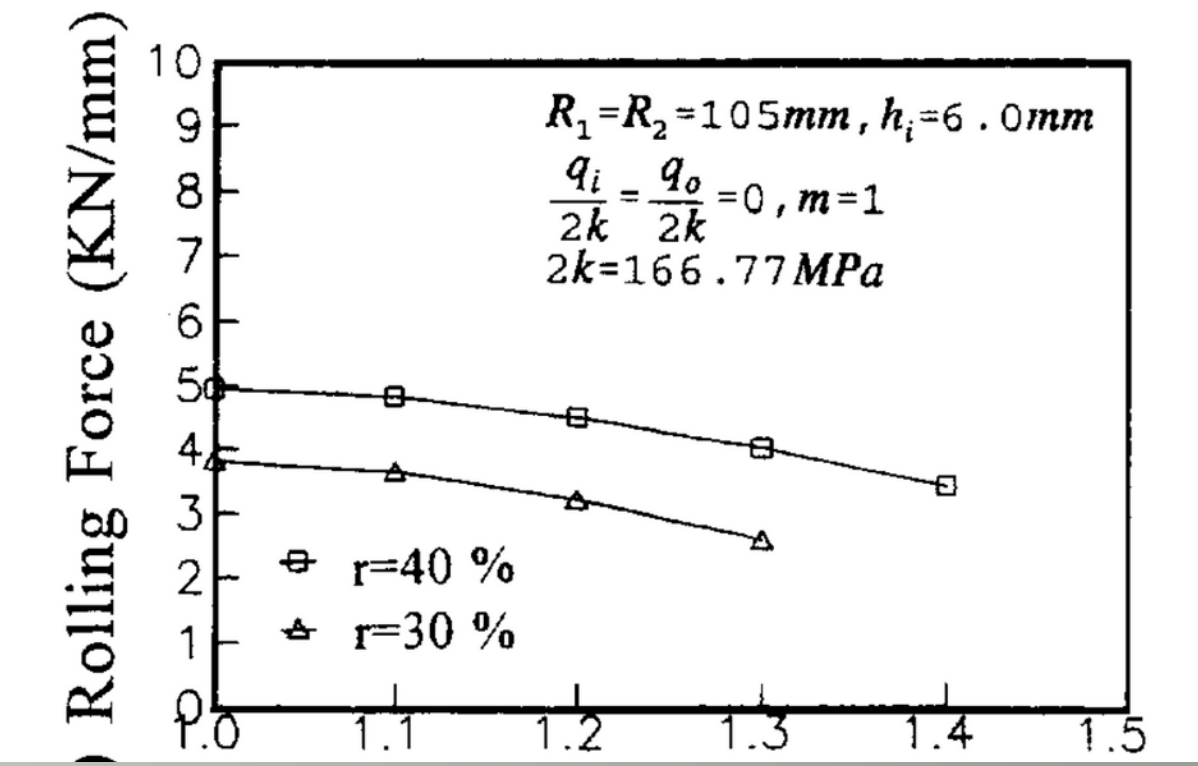
RESULTS AND DISCUSSION :

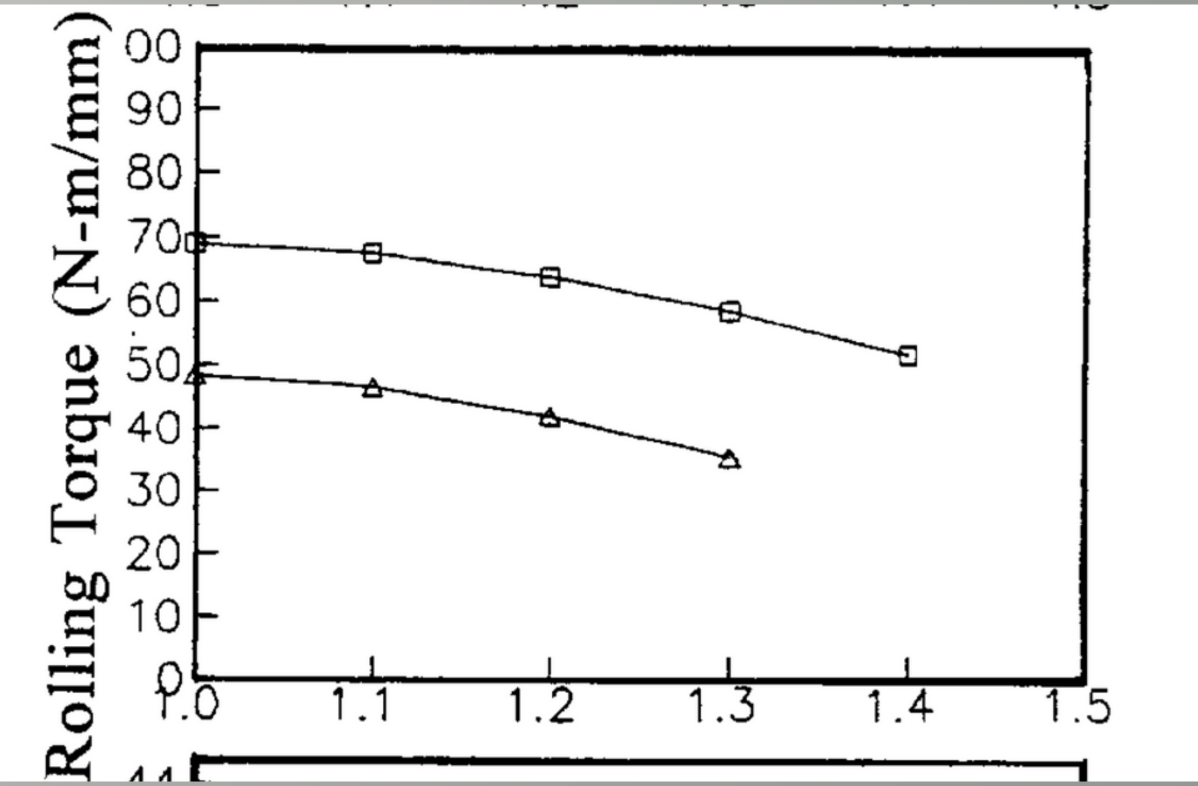
1.Rolling Force:

- The rolling force is observed to decrease as the roll speed ratio (V2/V1) increases. This suggests that increasing the speed of one roll relative to the other reduces the overall force required for rolling.
- However, as the thickness reduction increases (comparing curves for different reductions, such as 30% and 40%), the rolling force also increases. This is likely due to the increased material resistance as the sheet thickness decreases more substantially during rolling.

2.Rolling Torque:

- Similarly, the rolling torque decreases with an increasing roll speed ratio (V2/V1). This reduction in torque can be attributed to the reduction in the frictional force between the rolls and the sheet when one roll moves faster relative to the other.
- Higher thickness reduction (e.g., from 30% to 40%) results in a higher rolling torque, indicating that greater deformation requires more torque due to the additional resistance encountered during rolling.





Based on Neutral Points:

The decrease in rolling force and torque with increasing roll speed ratio can be associated with the shifting positions of the neutral points (denoted as xn1 for the upper roll and xn2 for the lower roll).

As V2/V1 increases, the neutral point xn2 (for the lower roll) shifts toward the exit, leading to a decrease in the rolling force and torque due to less resistance in the contact area.

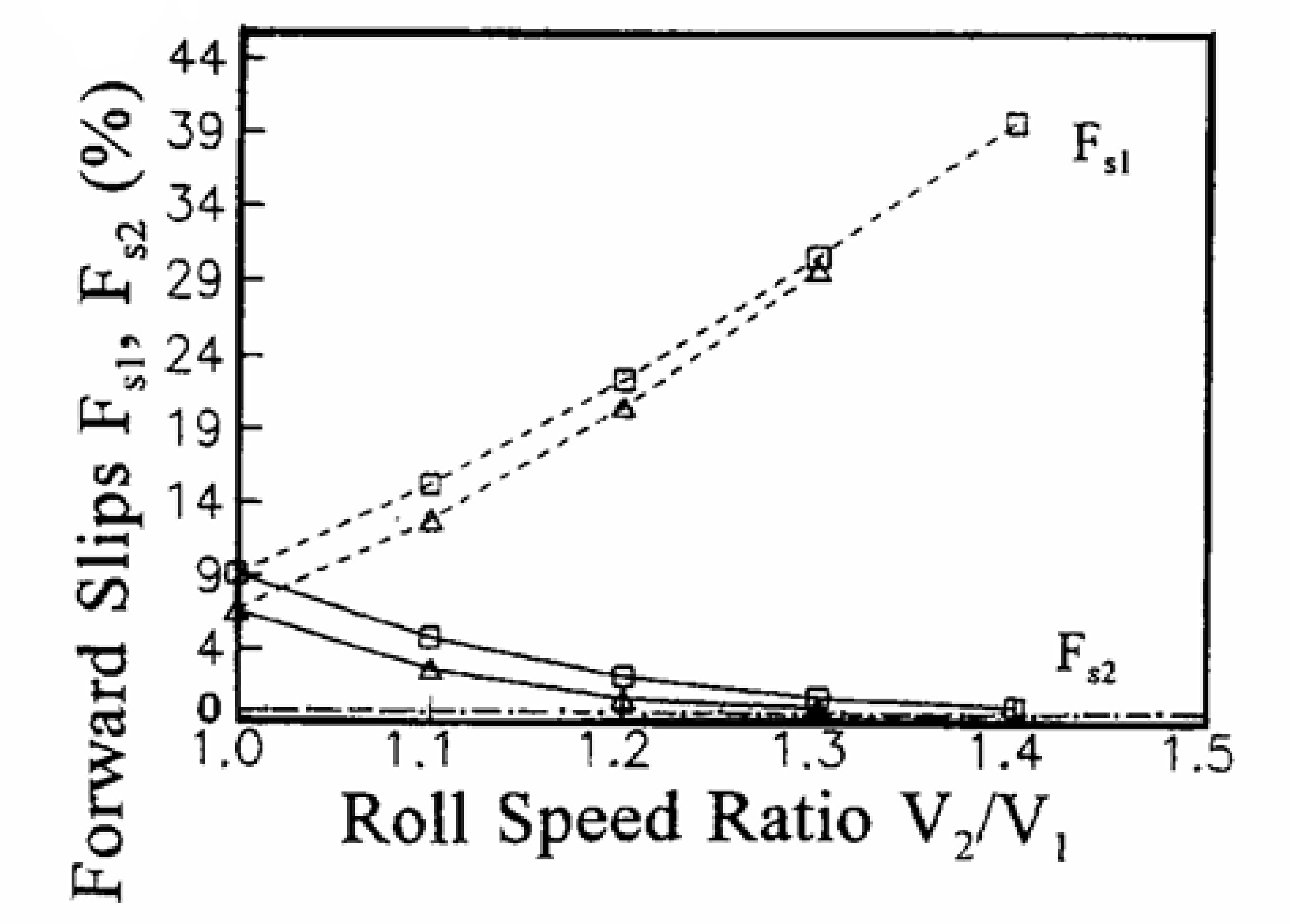
Conversely, xn1 for the upper roll moves towards the entrance, but the overall effect still results in a reduction of the rolling force and torque.

RESULTS AND DISCUSSION :

Forward Slip Percentage is the percentage of slip in leading zone. Leading zone is basically the zone which is after the neutral point.

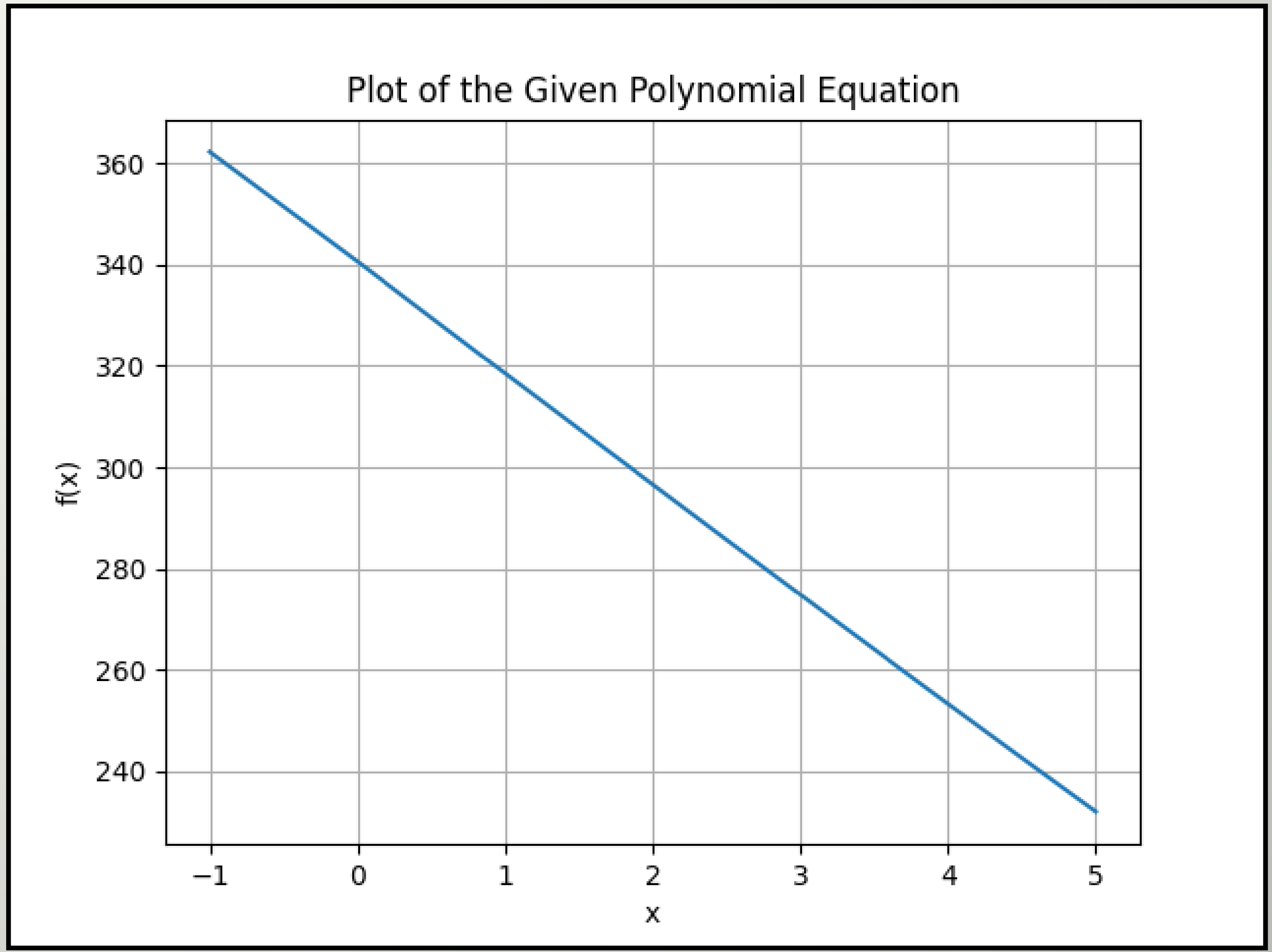
- Forward slips of the upper and lower roll (Fs1 and Fs2) are calculated by equations respectively. It indicates, evidently, that both the rolling force and rolling torque decrease with increasing roll speed ratio, whereas, they increase with the increase of the thickness reduction.
- The forward slip of the lower roll (Fs2) decreases with increasing V2/VI, whilst that of the upper roll (Fs1) increases with the increase of V2/V1 That is because Fs2 and Fs1 are related to the positions of neutral points (xn2 and xn1).
- When V2/VI increases, the neutral point of the lower roll (x,2) would move toward the exit and accordingly Fs2 decreases, whereas when V2/V1 increases, xn1 would move toward the entrance and accordingly Fs1 increases.
- It is noted that the rolling force, rolling torque, and forward slip of the upper and lower rolls (Fs1 and Fs2) increase with increasing r and m. As r or m increase, both of xn2 and xn1, move toward the entrance, and accordingly Fs2 and Fs1 increases.

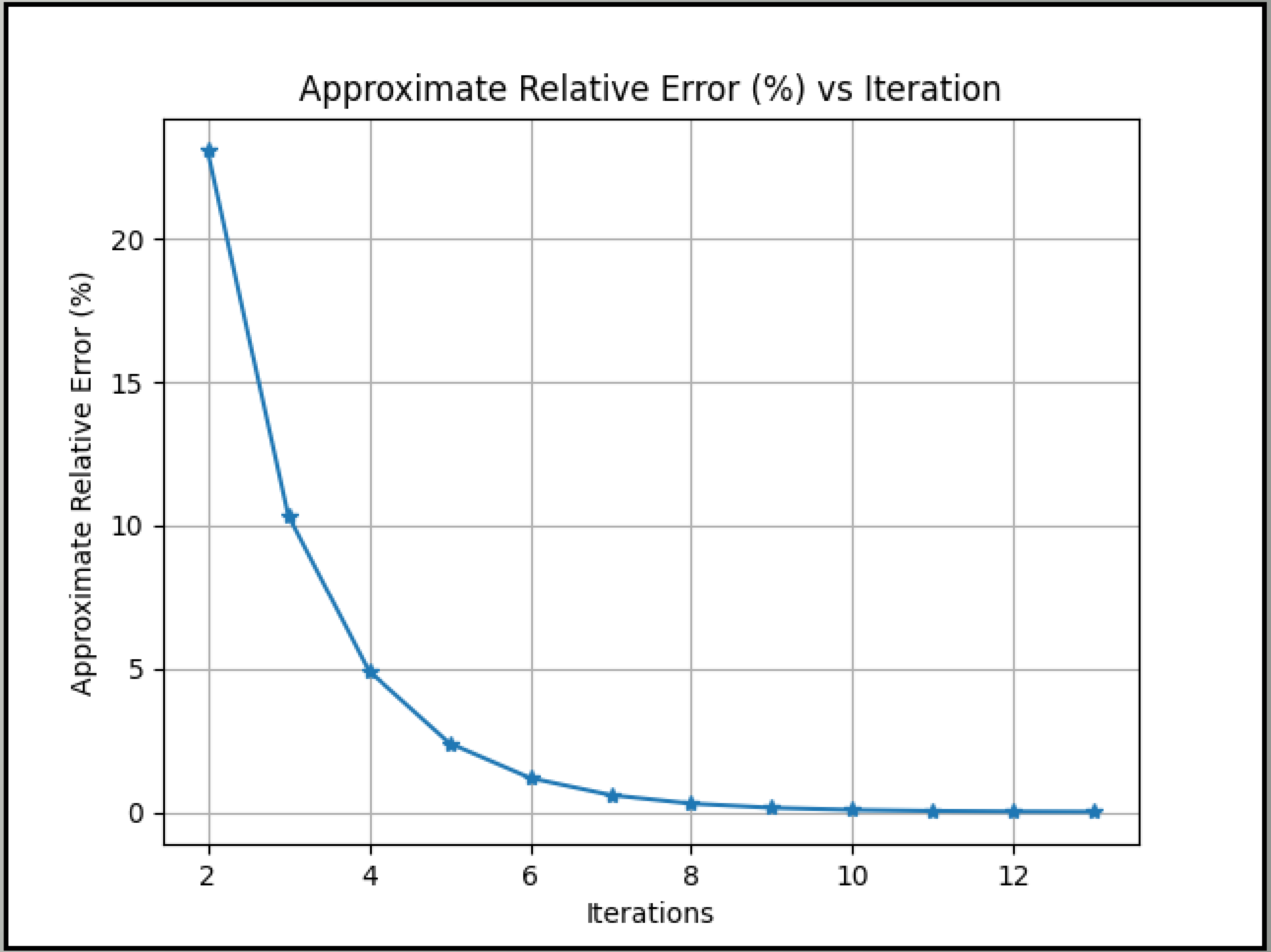
$$F_{s2} = \frac{(1 + F_{s1})}{V_2/V_1} - 1. \qquad F_{s1} = \left(\frac{1}{R_{eq} h_0} - \frac{1}{2R_{eq}^2}\right) x_{n1}^2 - \frac{x_{n1}^4}{2R_{eq}^3 h_0}.$$



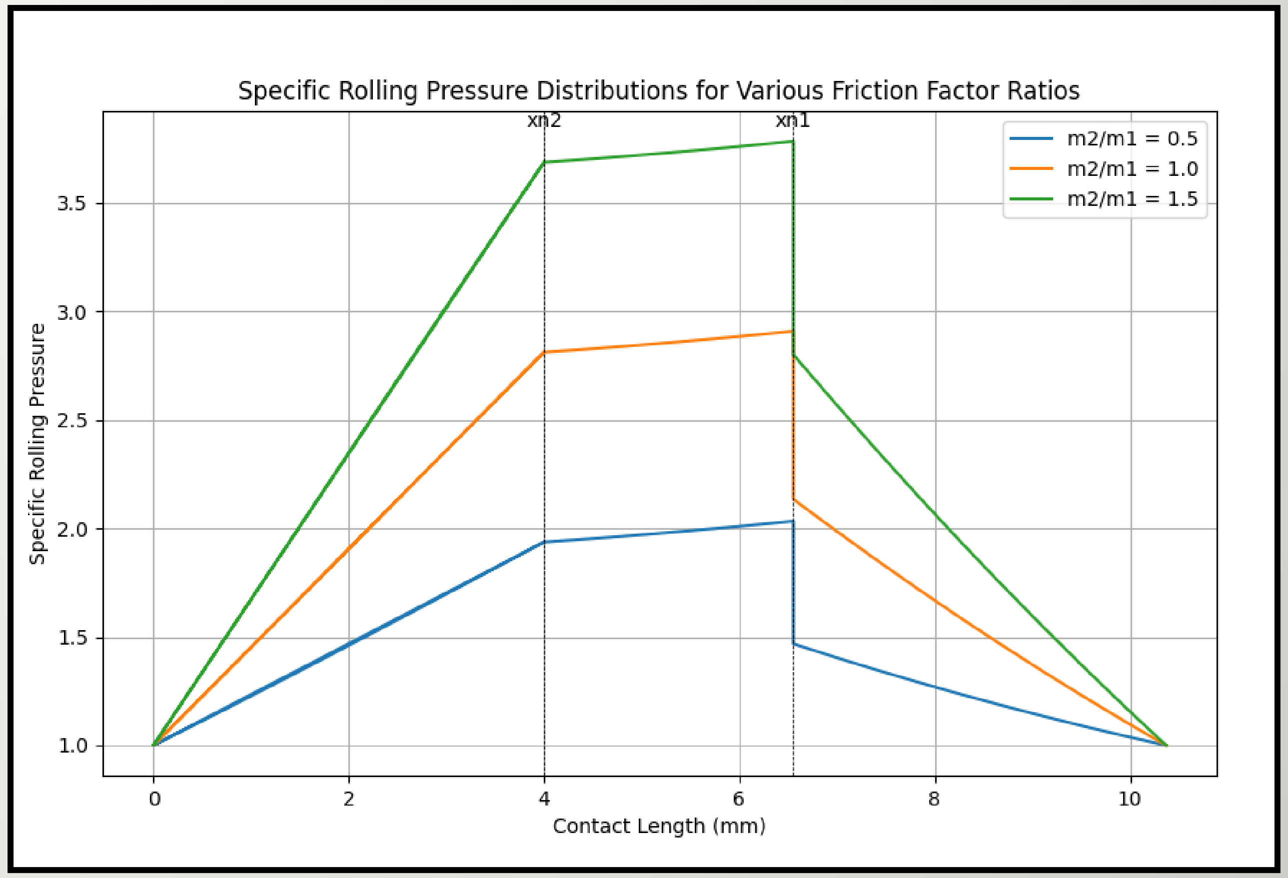
Calculation of Xn2 by Bisection method and Plot of the given function with Xn2

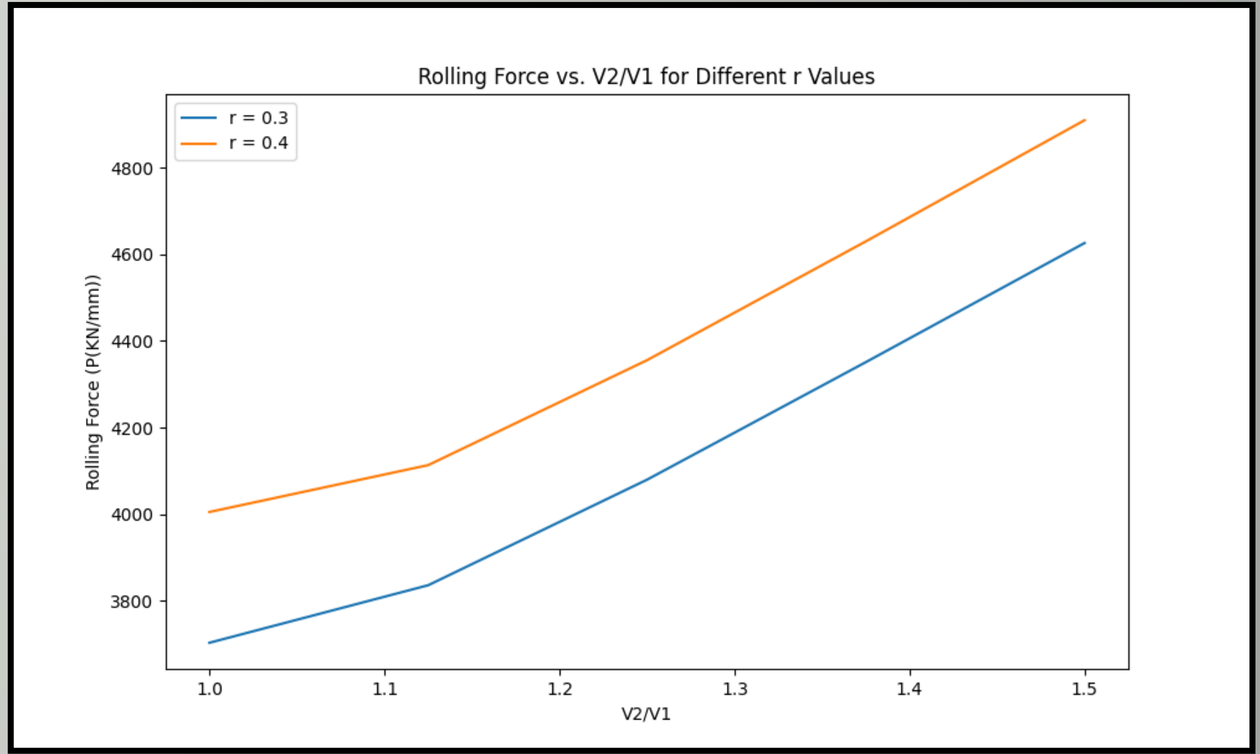
$$(A_2 - A_1)\,x_{n1} + E^*\omega_{n1} + c_1^* - (A_2 - A_3)\,x_{n2} - F^*\omega_{n2} - c_3^* = 0.$$

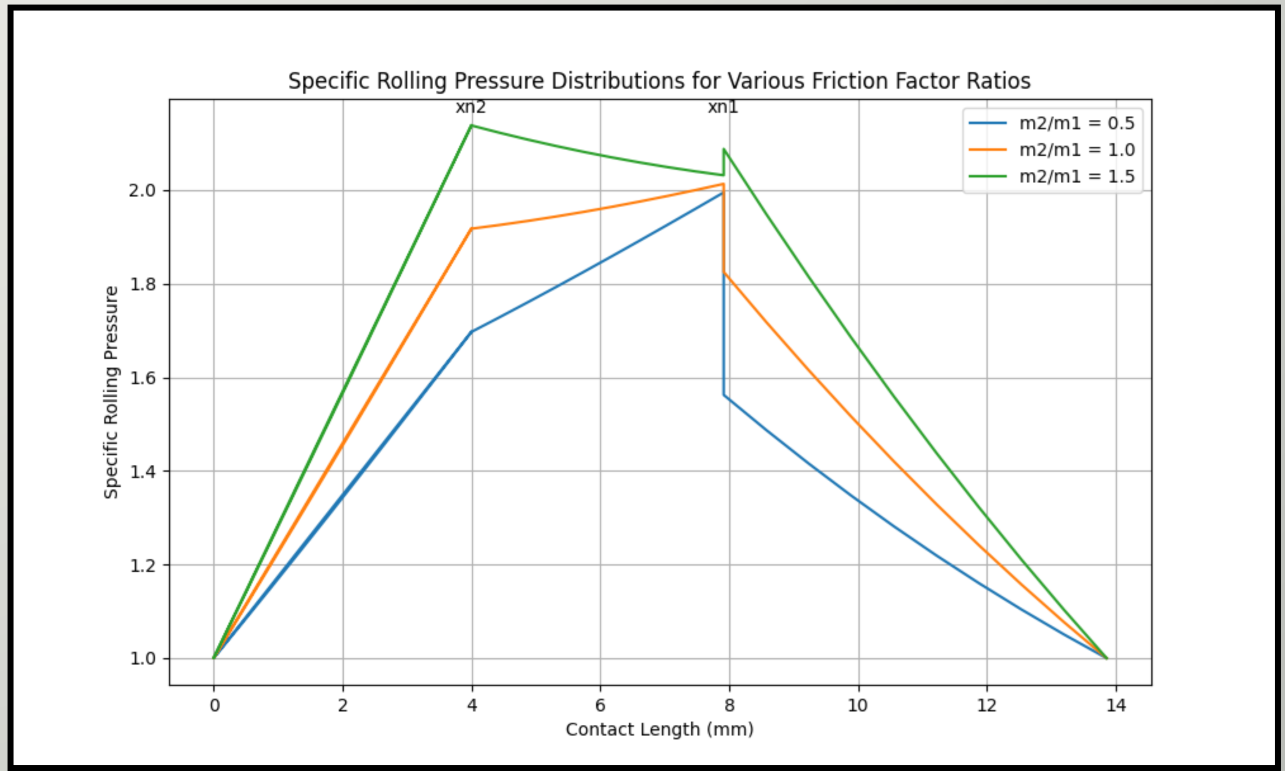


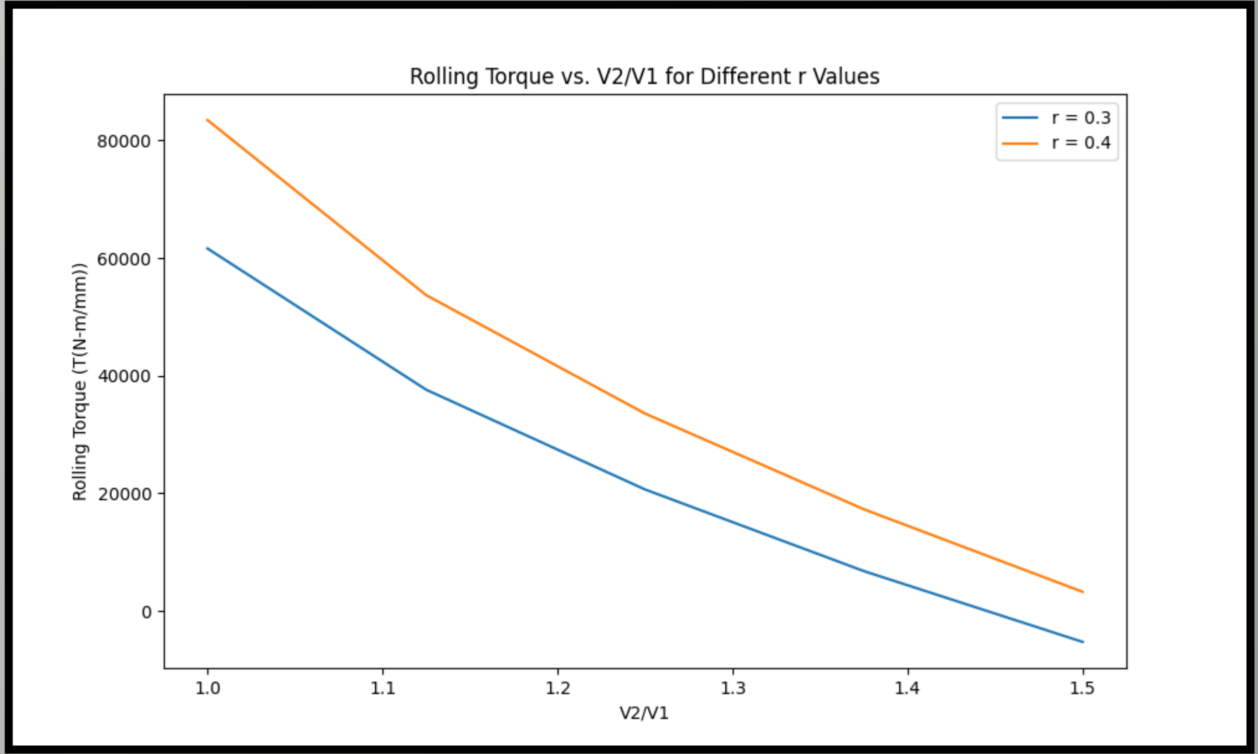


Results of Python Program:

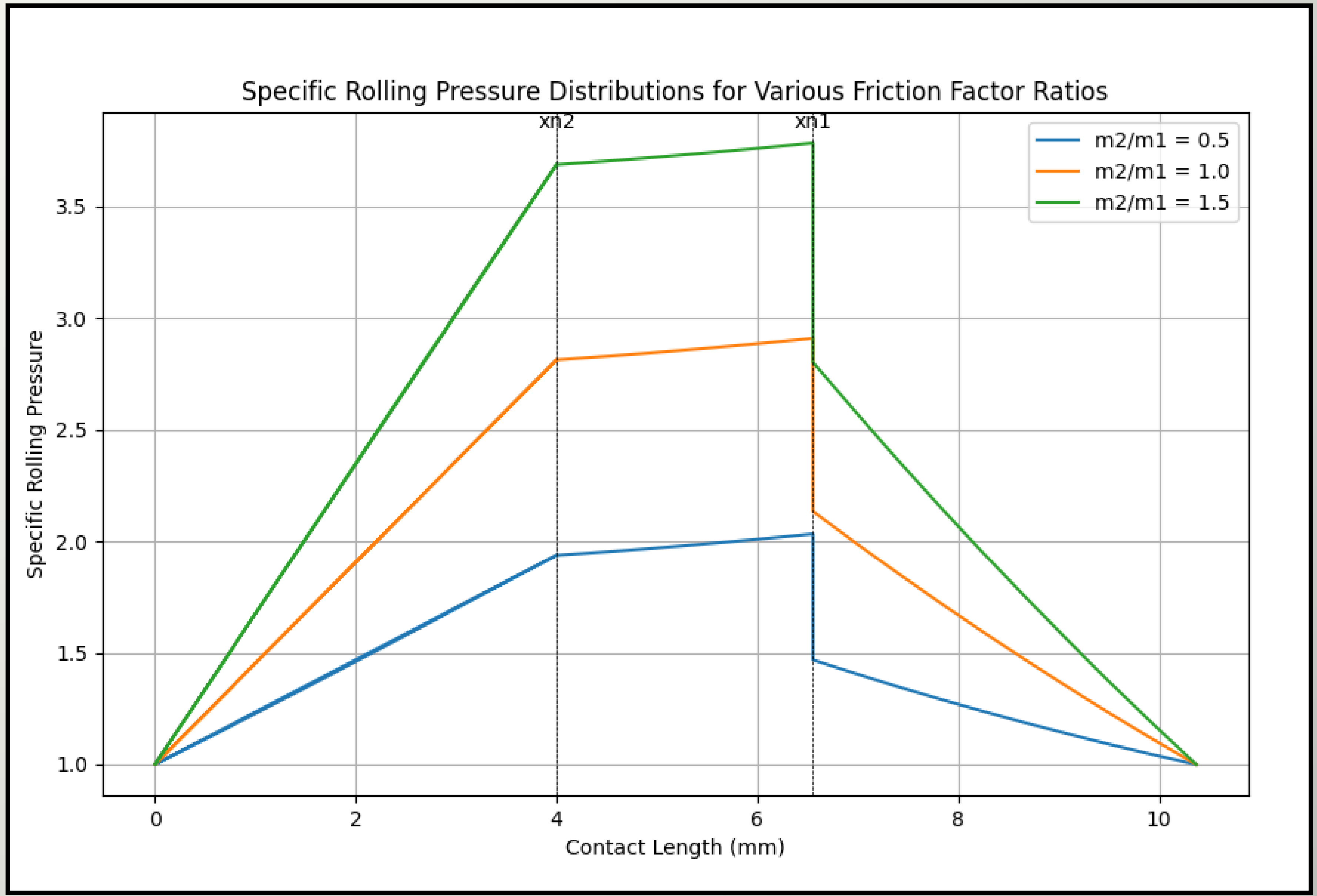








Plot of Specific Rolling Pressure and Contact Length for different m2/m1 ratio:



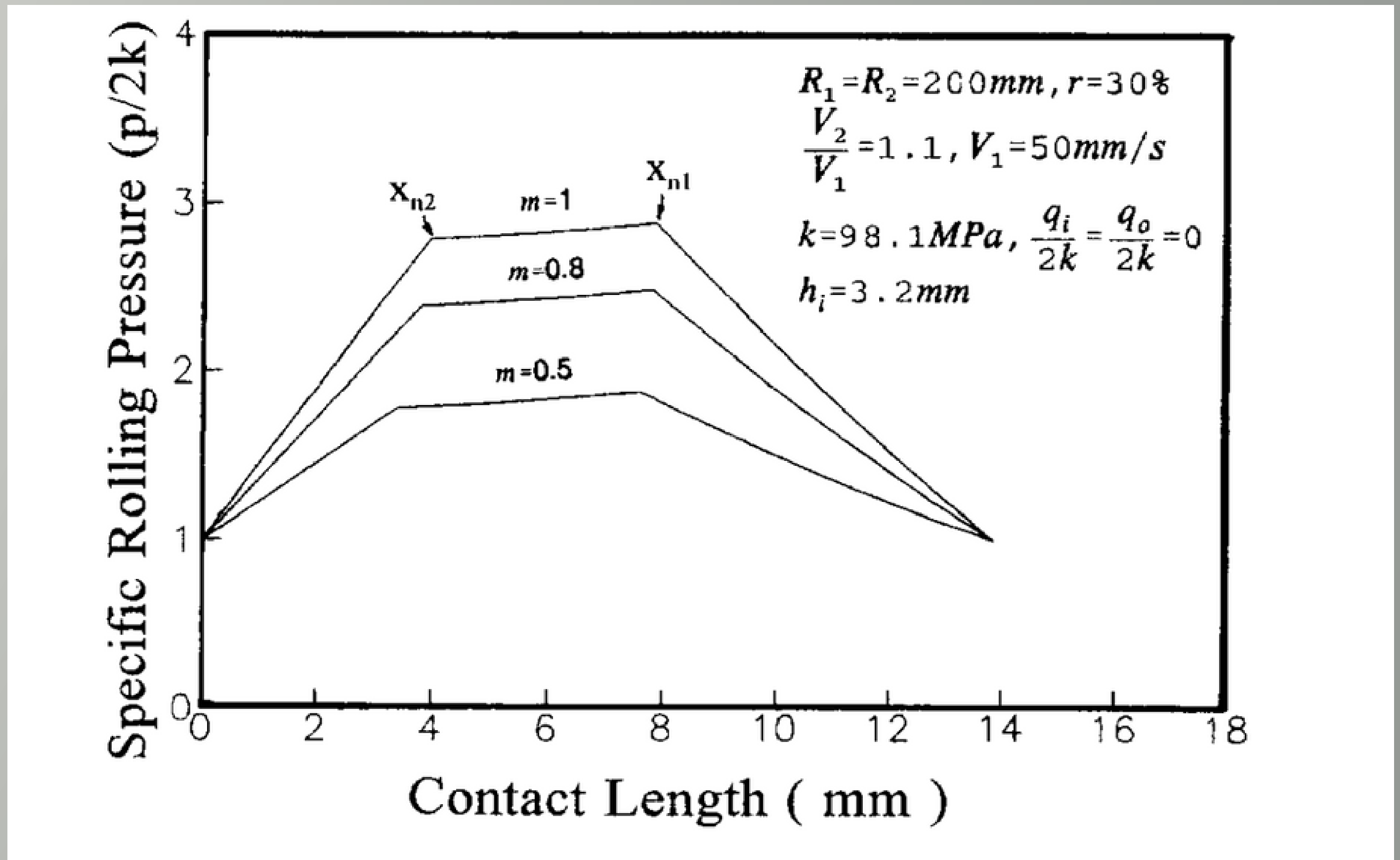
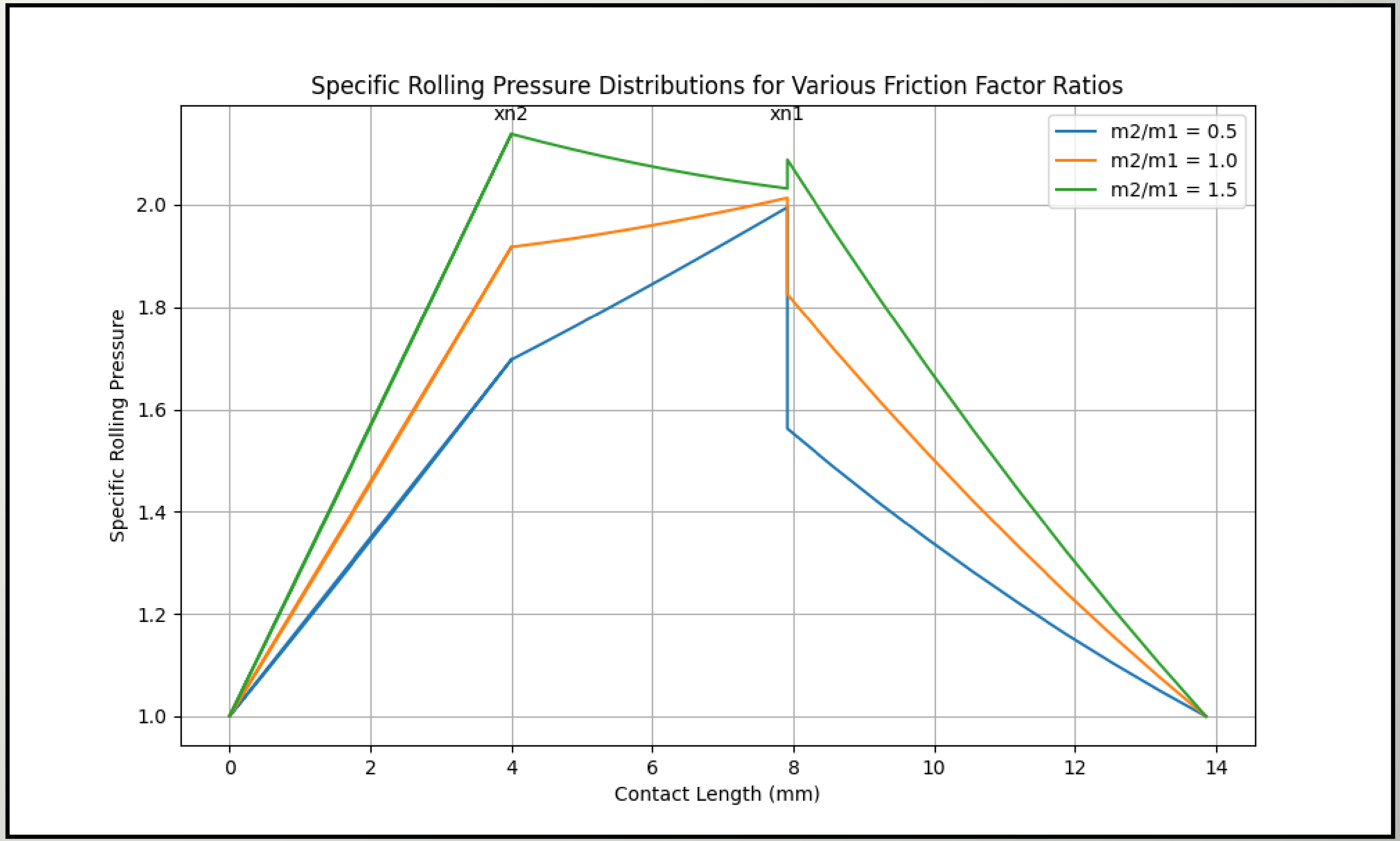
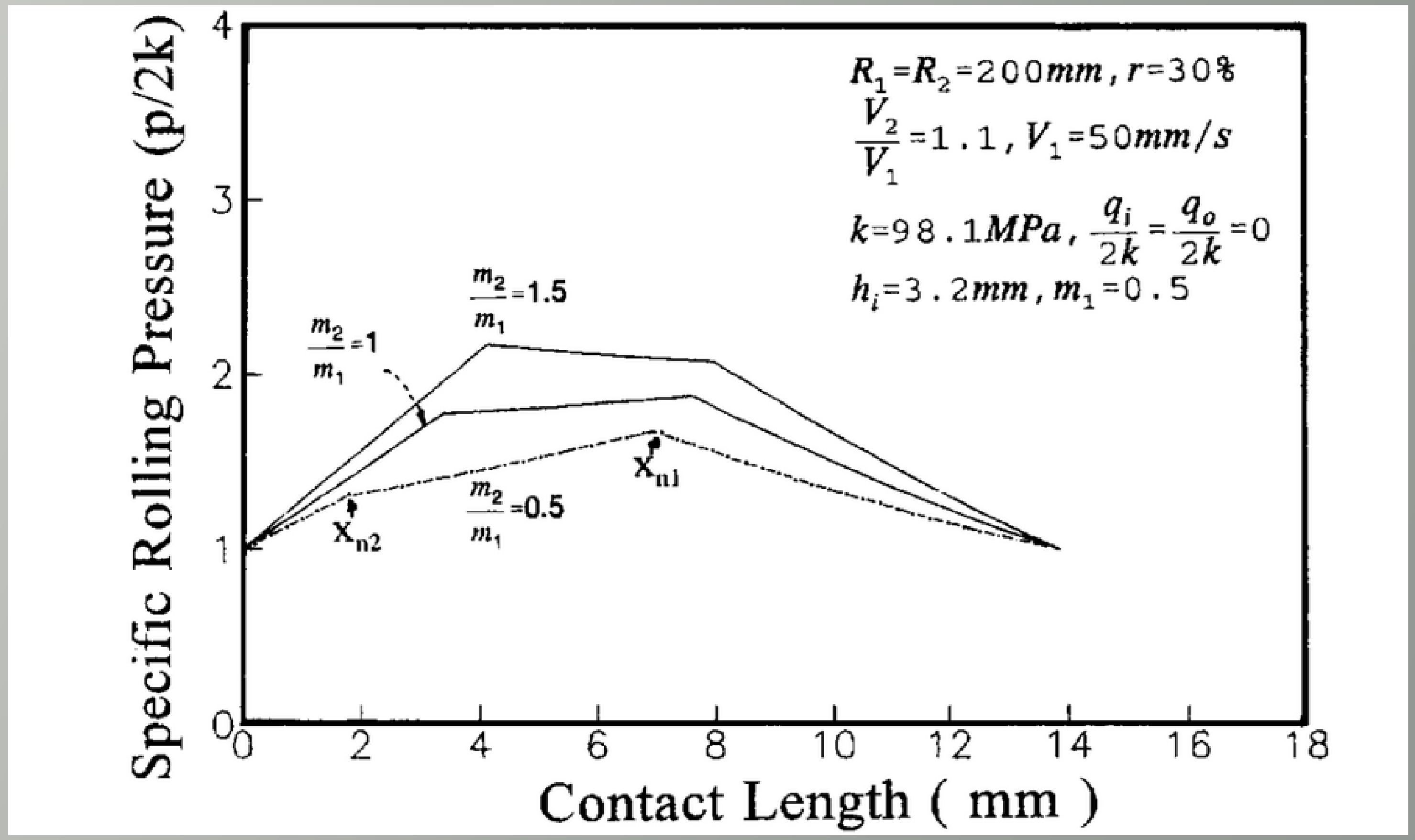


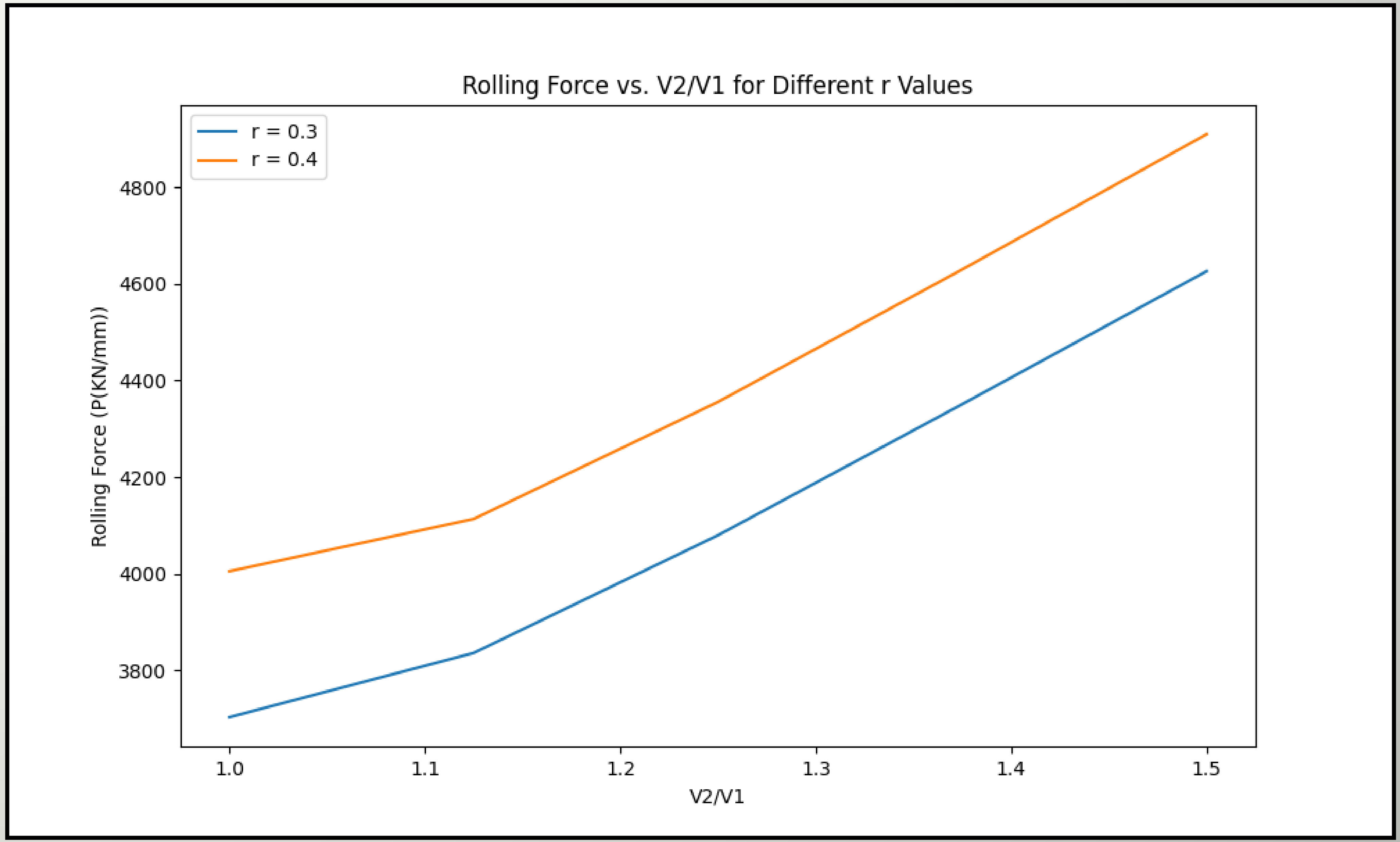
Fig. 3. The specific rolling pressure distributions for various friction factors.

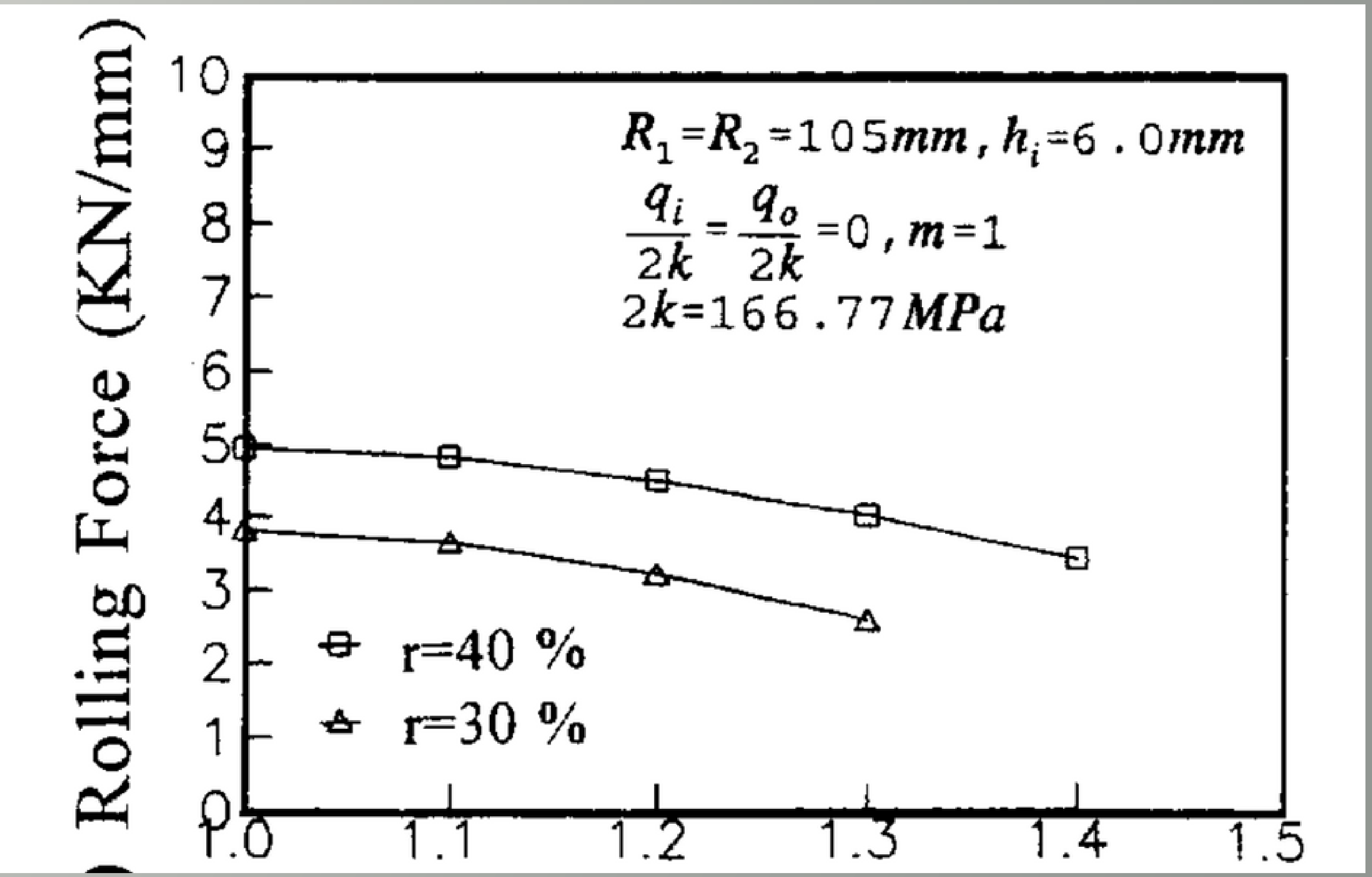
Plot of Specific Rolling Pressure and Contact Length for different m2/m1 ratio:



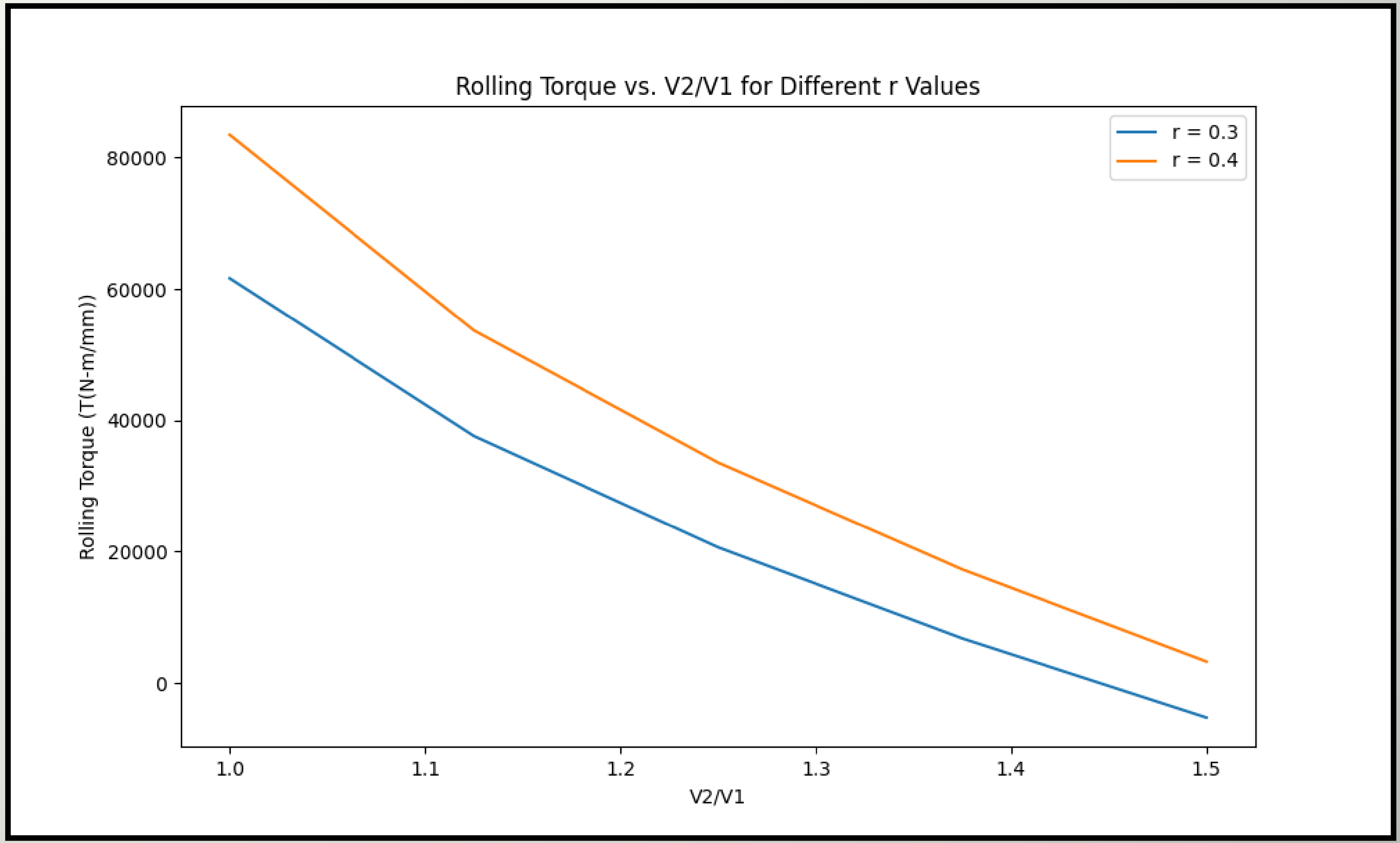


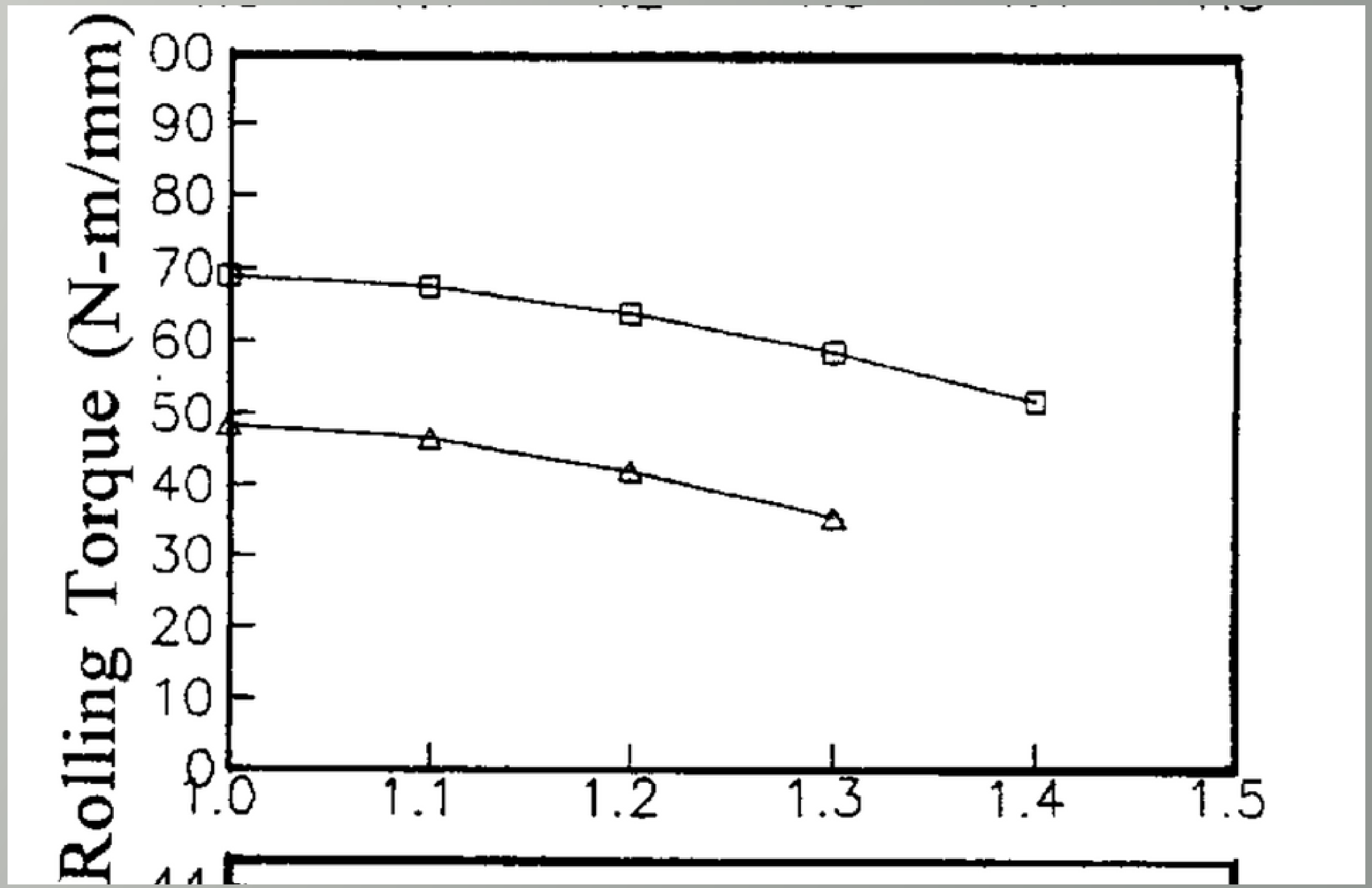
Plot of Rolling Force vs V2/V1 for different r values:





Plot of Rolling Torque vs V2/V1 for different r values:





Conclusion:

Efficiency and Validity: The analytical model provides fast and reliable calculations for rolling force, rolling torque, and forward slip in asymmetrical cold and hot sheet rolling.

Predictive Accuracy: Predicted rolling forces are slightly higher than experimental values due to the model not accounting for shear stress across the roll gap's vertical cross-section.

Error Margin: The maximum error between analytical and experimental results is approximately 15%, showing reasonable agreement.

Industrial Relevance: The model is well-suited for the rolling industry, offering a practical and efficient alternative to complex numerical analyses.

Friction Factor Evaluation: The forward slip method incorporated in this model allows for effective evaluation of friction factors, supporting improved pass schedule design in rolling processes.

Ambiguities in Research Paper:

1. All the plotings are done by keeping values of R1 & R2 equal.
2. Length of contact has taken equal between the sheet and upper and lower roll respectively but it should be different.
3. During the calculations of of final governing equation they didnt consider the p2*tanq2 value .

References:

1. W. Johnson and G. Needham, Further experiments in asymmetrical rolling. Int. J. Mech. Sci. 8, 443 (1966).
2. H. Yamamoto and T. Kawanami, Study on asymmetrical strip rolling (plasticine strain analysis). Proc. s-57 Sp. Conf. of Jap. Soc. Technol. Plasticity, 65 (In Japanese) (1982).
3. N. Kamii and R. Terakado, Study of the rolling method of hot finishing tandem mill by rolls with different diameters. J. Jap. Soc. Technol. Plasticity 17, 966 (1976).
4. H. Shiozaki, S. Shinya, M. Mikami and S. Koide, Experimental study on the effects of differential roll speed ratio on the rolling force, rolling torque and forward slip in thin strip rolling, d. Jap. Soc. Technol. Plasticity 23, 1080 (1982).
5. D. Pan and D. H. Sansome, An experimental study of the effect of roll speed mismatch on the rolling load during the cold rolling of the thin strip. J. Mech. Working Technol. 16, 361 (1982).
6. M. I. Ghobrial, A photoelastic investigation on the contact stresses developed in rolls during asymmetrical fiat rolling. Int. J. Mech. Sci. 31, 751 (1989).
7. S. Yariden, K. Kataoka and T. Watanabe, Analysis of behaviors of unequal roll speed cold rolling, Proc. 29th Joint Conf. of Jap. Soc. Technol. Plasticity, 127 (In Japanese) (1978).
8. H. Shiozaki and M. Mikami, Theory of differential work roll speed rolling based on the slip line field solution for the shearing compression of fiat plate. J. Jap. Soc. Technol. Plasticity 24, 25 (1983).
9. M. Kiuchi, S. H. Hsiang and Y. M. Hwang, Analytical model of asymmetrical roiling process of sheets. Proc. 4th Int. Steel Rolling Conf., F4.1 (1987).
10. G. R. Cao, F. R. Hall, P. Hartley and I. Pillinger, Finite element simulation of material flow in asymmetrical rolling process. Proc. 4th