

Innovative Roll Profile Design For Thin-Strip Cold Rolling Mills

Navneet Singh¹, Satish Kumar Tripathi², Manish Kumar¹, Amit Sharma¹, Vidyadhar Kelkar³

¹Digi Drives Pvt Ltd
148 Sector 58
Faridabad, Haryana, India 121004
Phone: +91 9810005675
Email: navneet@digidrives.in

²Yogiji Technoequip Pvt Ltd
Village Dudhola, District Palwal
Haryana, India 121102
Phone: +91 9958894842
Email: skt@yogiji.in

³Span Associates
29, Ramtekdi Industrial Estate Hadaspar
Pune, India 411028
Phone: +91 9822022084
Email: vidyadharkelkar@spanassociates.co.in

ABSTRACT

This paper presents a roll profile design to achieve greater reductions on a cold rolling mill to produce much lighter gauges in fewer passes without compromising strip shape. This study is based on the simulation of roll separating force applied on models with different roll profiles and analyzes the stress distribution across the rolls and the strip. The study also includes the thermal analysis of YOGIJI-DIGI-supplied 6-high reversing cold rolling mills with more pass reduction for similar incoming thickness compared to other mills and the significance of strip, coolant and roll temperatures in the cold rolling process.

Keywords: Cold Rolling Mills, 6HI, 4HI, Thin Strip Rolling, Strip Shape, Roll Profile

INTRODUCTION

This paper presents the innovative roll profile design to achieve greater reductions on a Cold Rolling Mill to produce much lighter gauges in lesser passes without compromising on strip shape. This study is based on the simulation of roll separating force applied on models with different roll profiles and analyses the stress distribution across the rolls and the strip. The study also includes the thermal analysis of YOGIJI-DIGI supplied 6-HI reversing cold rolling mills with more pass reduction for similar incoming strip thickness compared to other mills and the significance of strip, coolant and roll temperatures in the cold rolling process.

BACKGROUND

In the recent times, the market shift is towards reducing the finish gauges, conserve energy and of course increase production rates. Thin gauge rolling demand is increasing with increasing competition and pressure to reduce final equipment weight without compromising on strength. Thin strip used for roofing are also popular in certain markets in Asia and Africa to cater to low budget consumers.

The study is based on the optimised roll design of the 4-HI and 6-HI reversing cold rolling mills installed by YOGIJI-DIGI across the world producing relatively thinner gauges.

The most significant aspect of these mills is that they have more reduction compared to other mills for similar incoming hot strip thickness and final cold rolled strip thickness. The strip profile is relatively better and production rate is also higher in comparison.

The distinguished feature of these cold mills is that none of these mills use any heat exchanger to cool the rolling oil emulsion. This is in comparison to other mills where the cooler is typically designed to remove 50 to 60 percent of the heat load generated in the rolling operation based on the mill motor power¹.

FUNDAMENTALS OF COLD ROLLING AND HEAT GENERATION IN THE ROLLING PROCESS

In a cold rolling mill, it is the Arc of Contact between the hard work roll surface and the softer steel strip surface where friction is created and thus plastic deformation occurs and heat is generated².

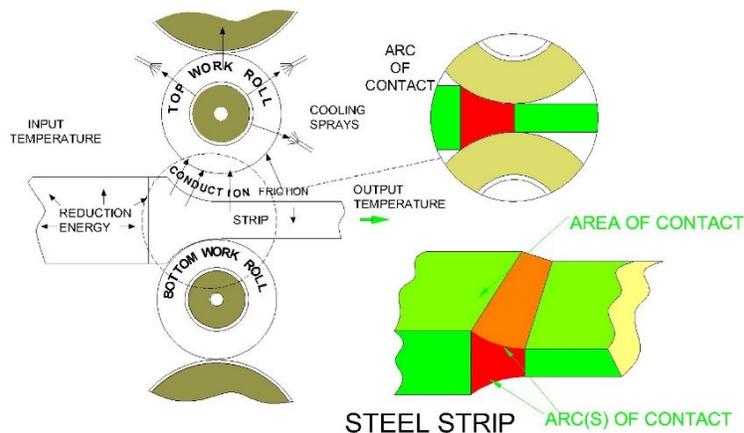


Figure 1. Roll Bite

Within the roll gap or the arc of contact, energy is distributed in to three main areas:

- Deformation energy uniformly distributed within the strip
- Frictional energy due to relative sliding between the roll and strip
- Heat transfer from the strip to the rolls due to temperature difference

The heat absorbed by the rotating roll is subject to a more complex mechanism. The heat will continuously migrate to cooler zones in the roll and out of the roll body at localized chill zones created by the coolant spray impingement on the roll surface.

The roll is subject to thermal and mechanical fatigue during rolling:

- Thermal fatigue as the roll cycles through the elevated temperature in the roll bite and lower temperature zones cooled under the coolant sprays
- Mechanical fatigue by mechanical compression (flattening) and physical deflection caused by the rolling force and the torque applied by the motor
- Also if the strip is very thin, the top and bottom work rolls may contact each other beyond the edges of the strip. It is a knownfact that the strip plastic deformation and roll deformation can be directly used in the control of strip shape and profile during rolling.

OPTIMIZATION OF ROLL SIZE TO REDUCE THE ROLL FLATENNING EFFECT

In any mill, it is not possible to roll with strip width equal to the roll face width. So, roll bending and roll flattening are two key phenomenon in the cold rolling process. The rolls act like beams as the separating force causes the rolls to bend and the amount of bending depends on the size and the length of the rolls and the strip width.

In a 6-HI Mill, the intermediate rolls can be laterally shifted to roll virtually any width of strip with any incoming profile at any roll separating force to nullify the roll bending movement but the roll bending cannot be eliminated.

The roll flattening will depend on:

- The total RSF (Roll Separating Force)
- Diameter of the roll – the exponent ratio of roll flattening to roll diameter is 3 to 2
- Face width of the roll or the roll contact outside the strip edges

With the market trends moving towards thinner gauge and high strength steels it was imperative to further optimize the cold rolling process to increase the reduction on the strip without compromising the strip quality.

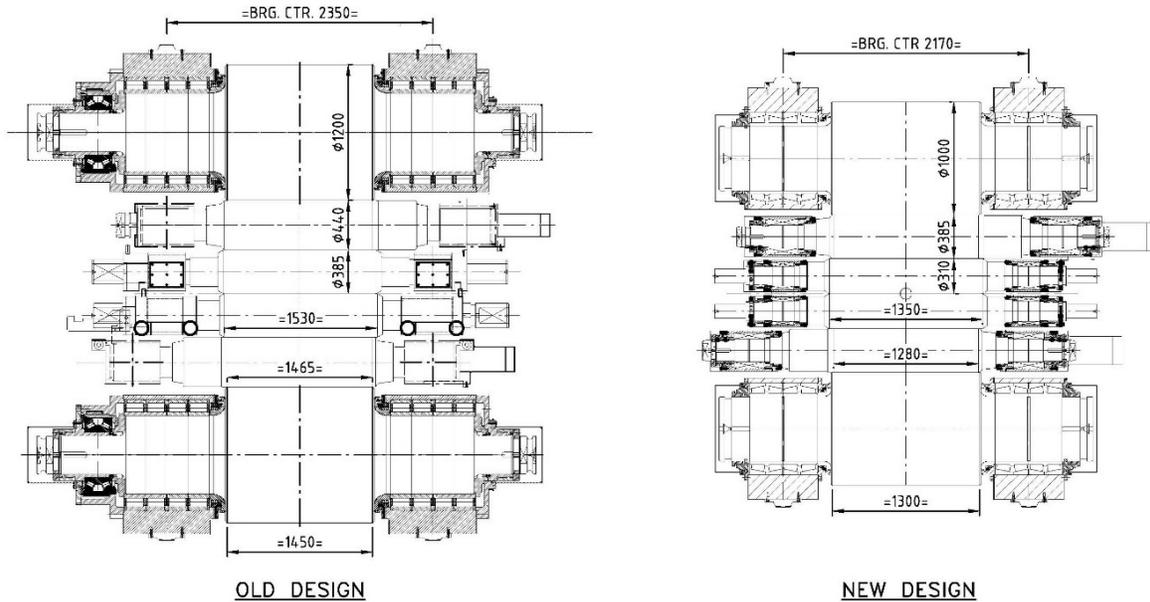


Figure 2. Comparison of the Existing and New Design for 1250 mm 6-HI CRM

The work roll barrel lengths in typical design of 4HI and 6HI mills are 13 to 22% more than the maximum strip width to be rolled.

YOGIJI-DIGI designed the work roll and back-up roll barrel lengths for both 4HI and 6HI cold rolling mills as below: If “x” is the strip width in mm

$$\text{Work Roll Barrel Length} = x + 100 \quad \text{Back Up Roll Barrel Length} = x + 50$$

The intermediate roll barrel length was designed to accommodate the minimum and maximum strip widths to be rolled.

The optimization of the roll barrel lengths further optimized the desirable same strip and roll width feature of the 6HI cold rolling mill.

The reduction in barrel lengths subsequently led to reduction of the bearing centres or the loading points which helped to improve the strip profile significantly.

SIMULATION OF STRESS ANALYSIS ON 6HI MILL STAND

A simulation study was made on the SOLIDWORKS Simulation Premium platform to analyse the effect of the roll profile and load centres on actual stress distribution on the strip and work rolls on a 6HI Cold Rolling Mill.

Table I. Study Properties

Analysis Type	Static
Mesh Type	Solid Mesh
Mesher Used	Blended curvature-based mesh
Jacobian Points	16
Maximum Element Size	80 mm
Minimum Element Size	16 mm
Mesh Quality Plot	High
Solver Type	Direct Sparse Solver
Soft Spring	On

A total load of 250,000 Kgf x 4 = 1,000,000 Kgf was applied to a strip of 1250mm wide and 0.5 mm thick on two models, one based on the roll profile used in a popular 6HI Cold Mill and other on the optimised Yogi-Digi design 6 HI Cold Rolling Mill.

The stress distribution on the strip was analysed and charted on a excel sheet across the width based on the tag elements generated by the simulation analysis.

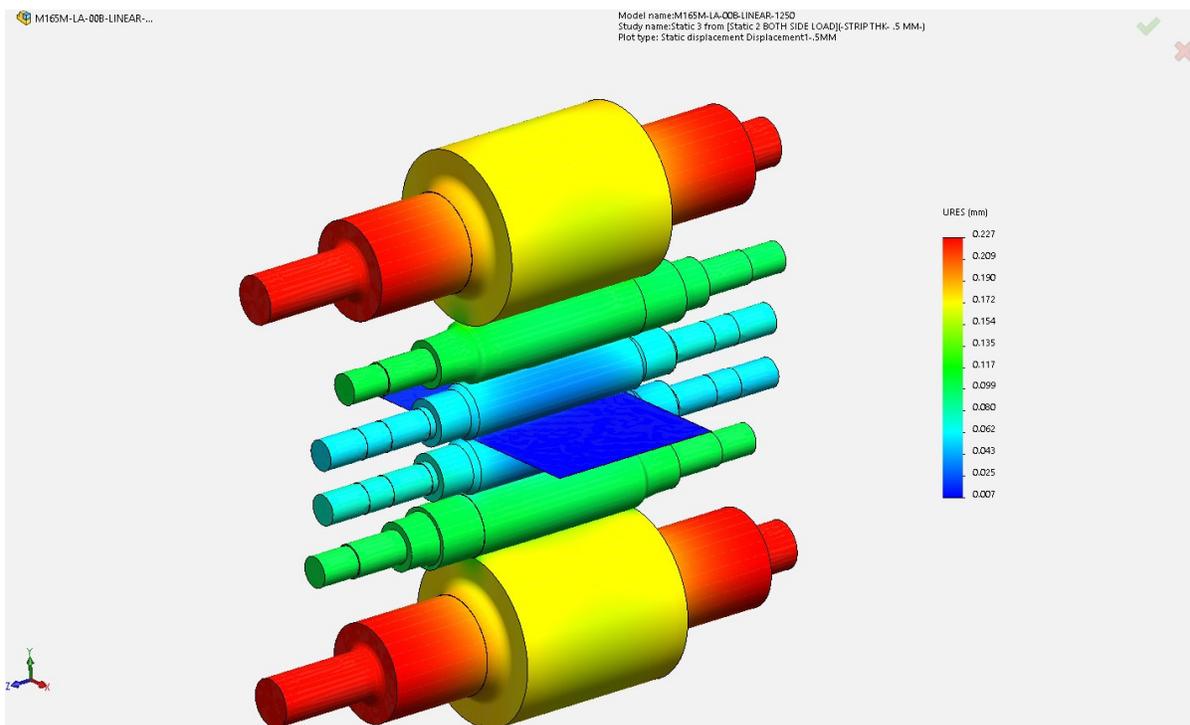


Figure 3. Simulation Model Configuration

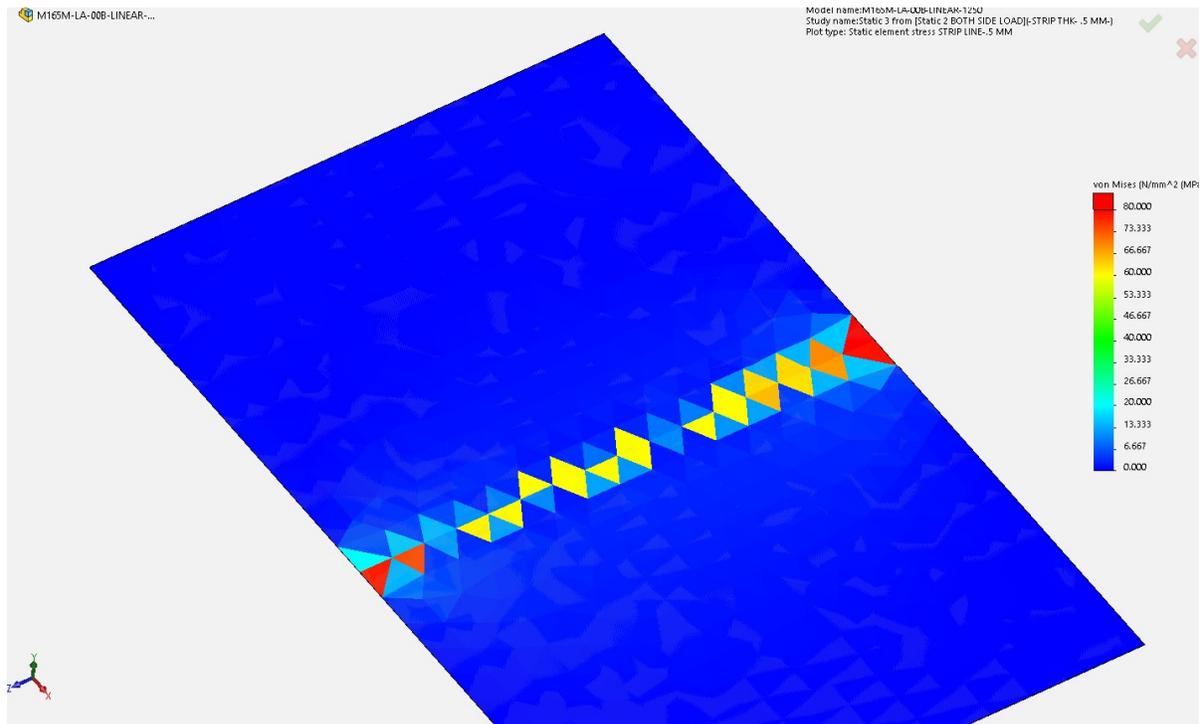


Figure 4. Stress Distribution on the strip on YOGIJI-DIGI Design 6HI Cold Mill.

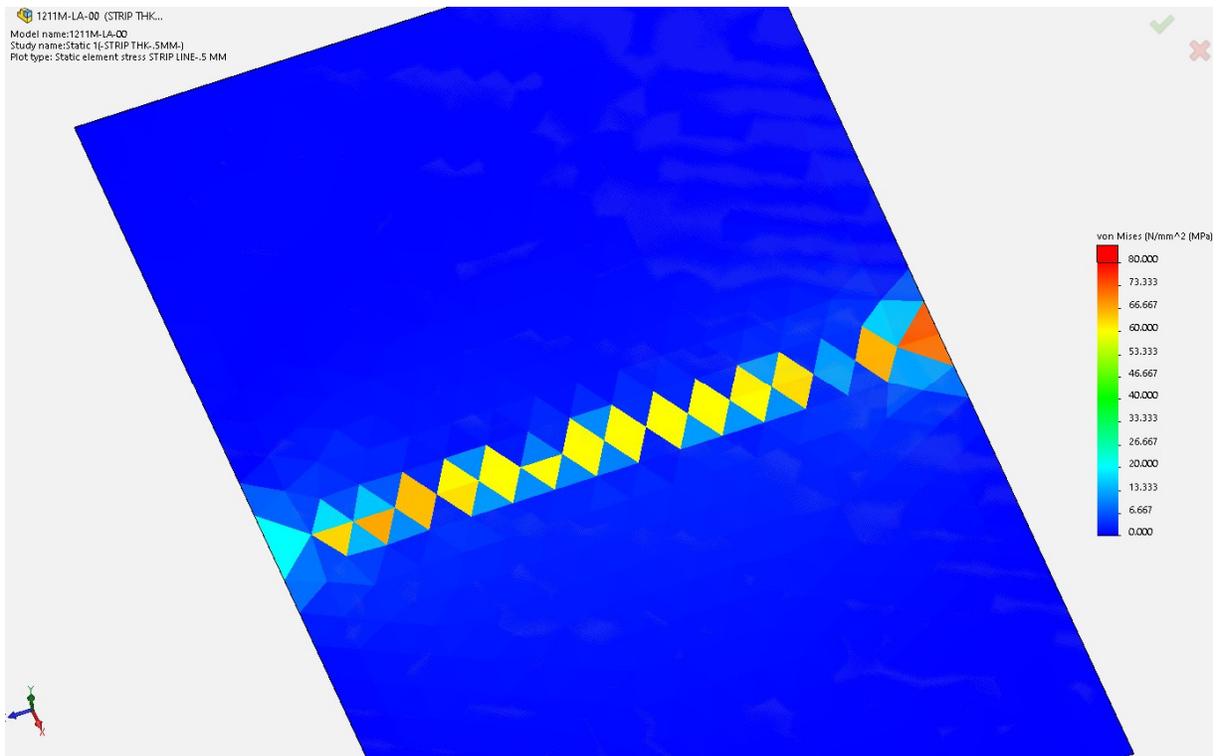


Figure 5. Stress Distribution on the strip on a Popular Design 6HI Cold Mill.

The stress distribution across the work roll was also charted and plotted as shown in Figure 6. This graphical representation of the stress distribution across the strip and work roll makes it clear that the stress distribution across the strip on the optimised mill is quite uniform. It is also notable to observe that there is sharp edge drop-off on the standard mill due to more bending movement of the rolls.

The strip stress analysis also suggests the optimisation of the roll profile resulted in 15% more stress on the strip and thus more pass reduction and a uniform stress distribution across the width, which would in turn ensure a better strip profile.

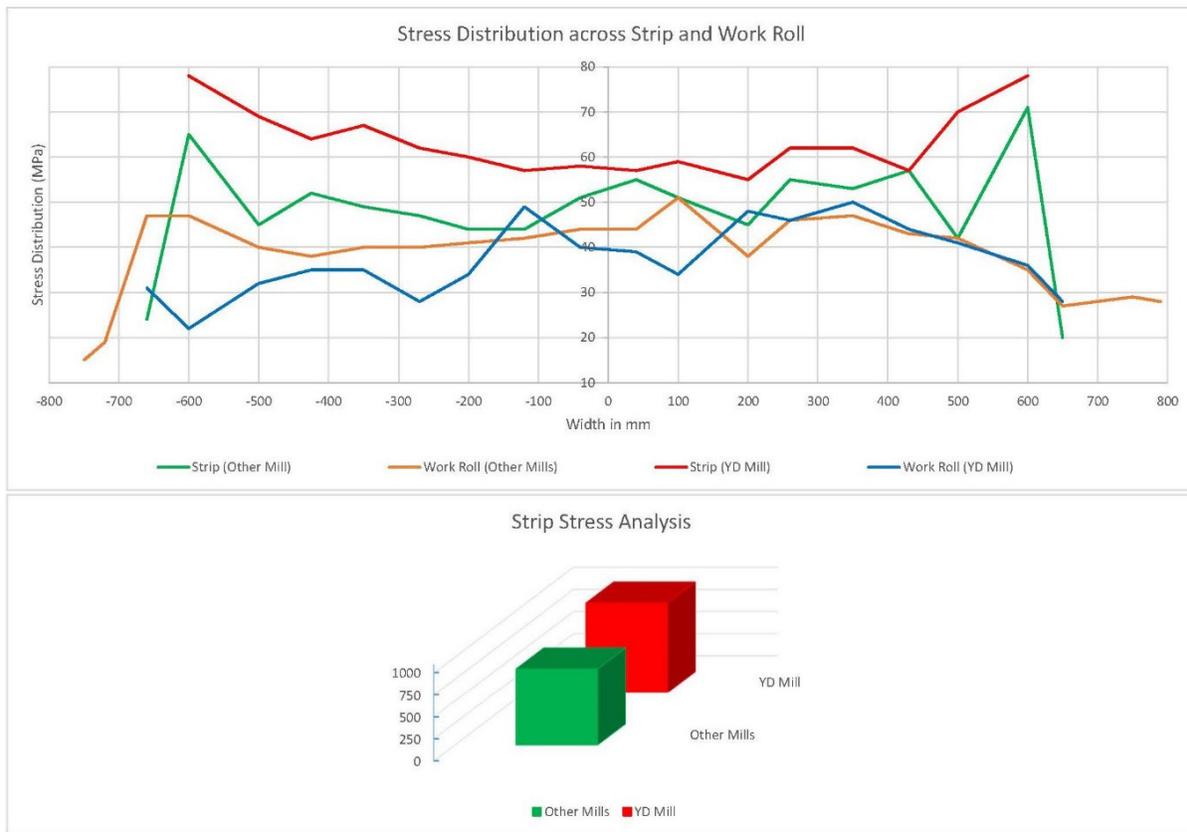


Figure 6. Stress Distribution Analysis across the strip and work rolls

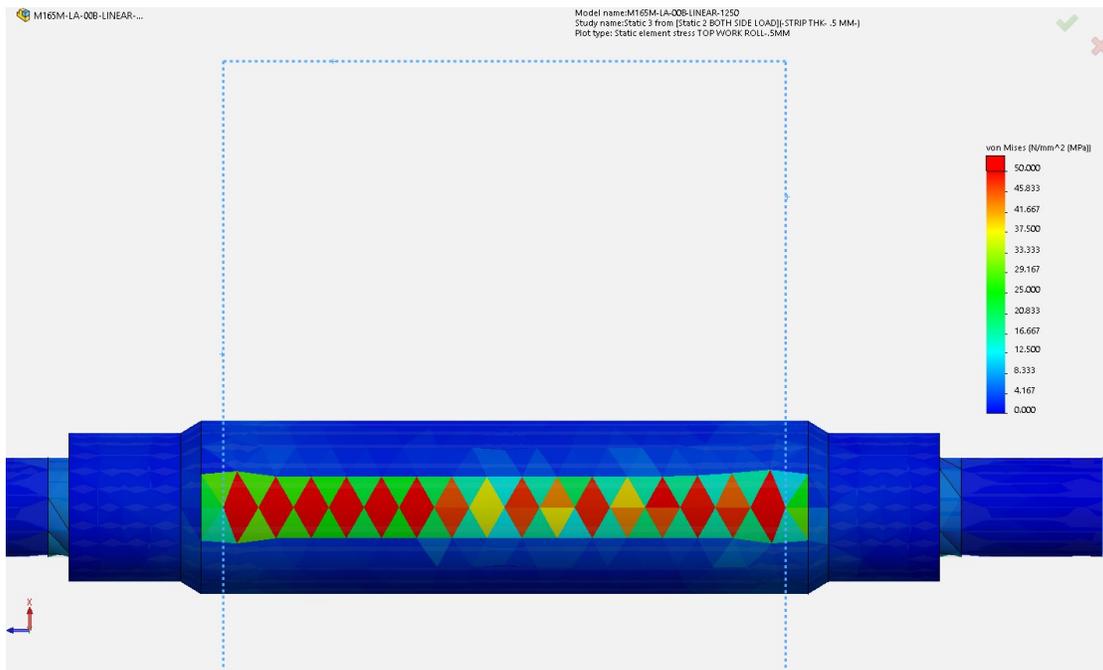


Figure 7. Stress Distribution on work roll on YOGIJI-DIGI Cold Mill

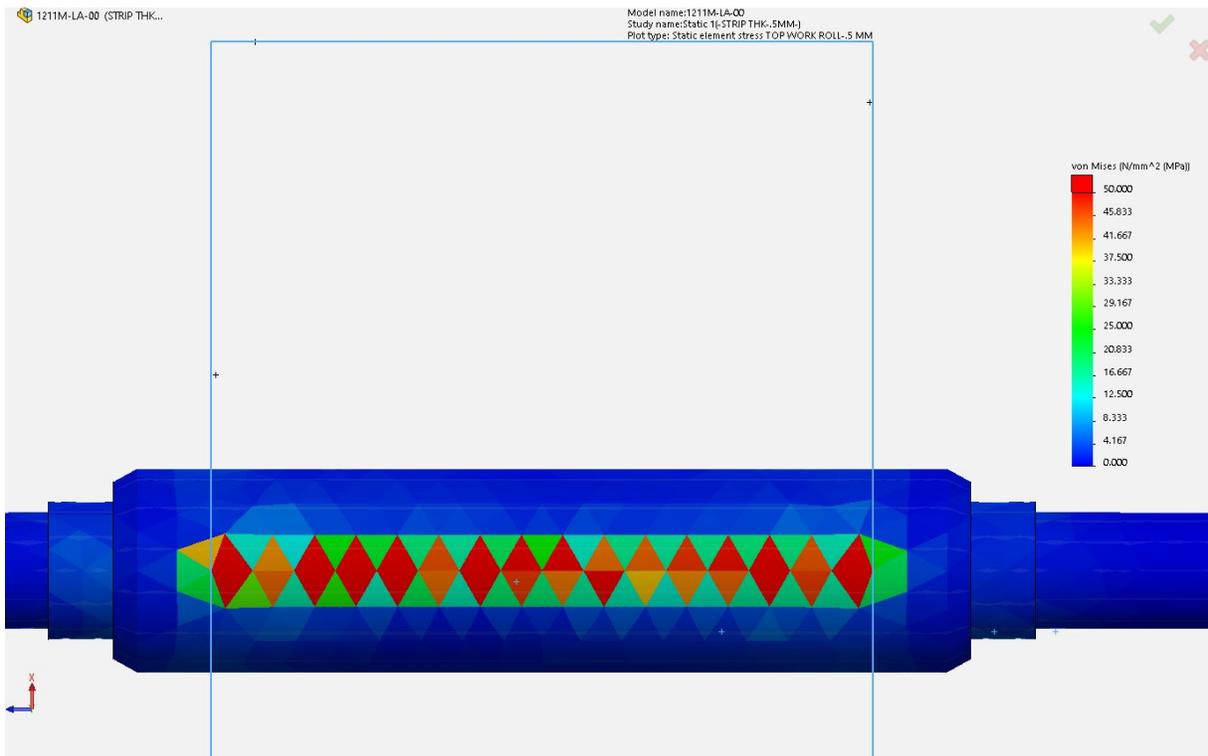


Figure 8. Stress Distribution on work roll on a Standard 6 HI Cold Mill

The roll stress distribution indicates that the stress on the work rolls in the optimised roll profile design is lower which means the rolls are subject to lower mechanical and thermal fatigue.

MILL THERMAL ANALYSIS AND MECHANICS OF ROLLING

A thermal analysis was conducted on three different reversing cold rolling mills supplied by YOGIJI-DIGI for different output thickness.

It is interesting to see that the energy going in to the strip reduction is between 55 to 80 percent compared to 48 to 59 percent in other mills. This can be identified in Table II which compiles the distribution of the supplied mill power for three different mills.

Also the energy going in to the friction and conduction is significantly lower if compared to other mills.

The data clearly shows that with the optimized roll profile the coolant evaporation losses are negligible, which for a conventional mill is around 7%

For a typical mill power of 3000kW,

The water saved on account of coolant evaporation = 210 (kW) X 860/540 = 334 litres per hour

The amount of water saved on account of elimination of the heat exchanger of 6000 lpm for this mill would be 200 litres per hour.

So, the total water saved is 534 litres per hour or 3.2 million litres of water per year or 846,000 US gallons every year.

Moreover, more the reduction energy going in to the strip means more the strip temperature. This increase in strip temperature will cause decrease in material yield stress which is the result of the increase in the strain rate.

The more energy going in to the strip means more reduction on the strip and hence, less number of passes to reach the final thickness from similar input thickness.

Coil Rolling Data - 6HI-CRM, 1250mm Wide @ 800MPM													
Sr No	Strip Width (mm)	Pass Number	Entry Thickness (mm)	Exit Thickness (mm)	Reduction (%)		Pass Time (Hour:min)	Rolled Tonnage	Strip Temp (Deg)	Coolant Level (Litre)	Coolant Temp (Deg)	KWH Consumed (KWH)	
Coil -1 Data													
Coil Temperature before Rolling									31				
1	1020	1	1.800	1.310	27.2		0:06	14.43	60	65,000	46	138	
		2	1.310	0.969	26.0		0:03	14.43	85	64,650	46	139	
		3	0.969	0.712	26.5		0:04	14.43	95	64,100	47	165	
		4	0.712	0.522	26.7		0:06	14.43	95	63,500	47	184	
		5	0.522	0.382	28.8		0:07	14.43	98	62,300	48	221	
Sum						0.46	0:28	72.15	67	63,910	2	847	
Per Hour Results									156.85	67	2,700	Power Per	1,841
Losses during Rolling									In Kcal		In KWH	In %	
Heat Transfer to Strip									12,66,703		1,472.91	80.0	
Heat Transfer to Coolant									1,27,820		148.63	8.1	
Heat Transfer to Coolant Volume Loss									1,463		1.70	0.1	
Other Conduction Losses									1,87,535		218.06	11.8	
COIL -2 Data													
Coil Temperature before Rolling									30				
2	1020	1	1.800	1.310	27.2		00:06	14.52	65	62,100	48	134	
		2	1.310	0.969	26.0		00:03	14.52	85	62,000	48	138	
		3	0.969	0.712	26.5		00:04	14.52	102	60,500	49	168	
		4	0.712	0.522	26.7		00:06	14.52	97	60,000	49	181	
		5	0.522	0.382	28.8		00:08	14.52	98	59,000	49	226	
Sum						0.47	0:29	72.6	68	60,720	1	847	
Per Hour Results									154.47	68	3,100	Power Per	1,802
Losses during Rolling									In Kcal		In KWH	In %	
Heat Transfer to Strip									12,58,606		1,463.50	81.2	
Heat Transfer to Coolant									60,720		70.60	3.9	
Heat Transfer to Coolant Volume Loss									1,680		1.95	0.1	
Other Conduction Losses									2,28,824		266.07	14.8	
COIL -3 Data													
Coil Temperature before Rolling									30				
3	1020	1	1.800	1.310	27.2		0:13	13.20	65	59,000	49	128	
		2	1.310	0.969	26.0		0:11	13.20	85	58,700	49	129	
		3	0.969	0.712	26.5		0:12	13.20	95	58,000	50	156	
		4	0.712	0.522	26.7		0:14	13.20	97	57,100	50	165	
		5	0.522	0.382	28.8		0:18	13.20	98	56,100	51	204	
Sum						0.47	1:08	66	68	57,780	2	782	
Per Hour Results									140.43	68	2,900	Power Per	1,664
Losses during Rolling									In Kcal		In KWH	In %	
Heat Transfer to Strip									11,42,502		1,328.49	79.8	
Heat Transfer to Coolant									1,15,560		134.37	8.1	
Heat Transfer to Coolant Volume Loss									1,572		1.83	0.1	
Other Conduction Losses									1,71,260		199.14	12.0	

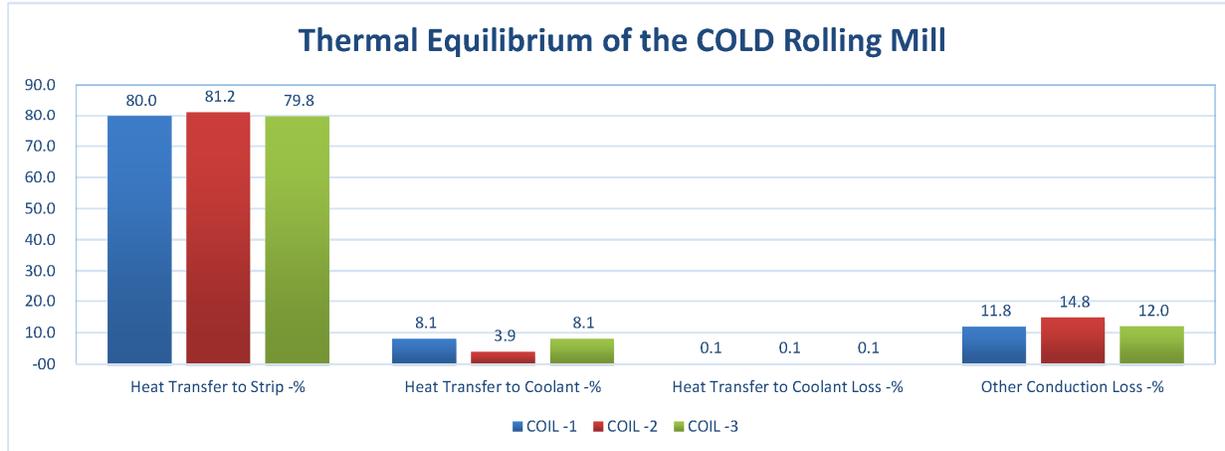


Figure 9. Sample Data from 6HI CRM 1250 mm x 800 mpm

Coil Rolling Data - 6HI-CRM, 1250mm Wide @ 1200MPM													
Sr No	Strip Width (mm)	Pass Number	Entry Thickness (mm)	Exit Thickness (mm)	Reduction (%)	Pass Time (Hour:min)	Rolled Tonnage	Strip Temp (Deg)	Coolant Level (Litre)	Coolant Temp (Deg)	KWH Consumed (KWH)	Workroll Temp	
Coil -1 Data													
1	765	Coil Temperature before Rolling							30				
		1	2.100	1.500	28.6	0:04	14.5	64	21,600	53.0	130	50.2	
		2	1.500	1.000	33.3	0:07	14.5	105	21,600	53.0	206	51.0	
		3	1.000	0.665	33.5	0:11	14.5	118	20,700	54.0	239	50.9	
		4	0.665	0.440	33.8	0:10	14.5	120	20,700	54.0	266	50.0	
		5	0.440	0.291	33.9	0:12	14.5	124	19,800	54.2	309	51.0	
		6	0.291	0.195	33.0	0:15	14.5	129	18,900	55.0	389	51.2	
		7	0.195	0.125	35.9	0:19	14.5	130	18,900	55.0	457	52.0	
Losses during Rolling								In Kcal		In KWH	In %		
Heat Transfer to Strip								7,20,710		838.03	54.6		
Heat Transfer to Coolant								40,629		47.24	3.1		
Heat Transfer to Coolant Volume Loss								1,463		1.70	0.1		
Other Conduction Losses								5,57,629		648.41	42.2		
COIL -2 Data													
2	765	Coil Temperature before Rolling							30				
		1	2.100	1.500	28.6	0:04	14.5	64	21,600	55	124	50.9	
		2	1.500	1.000	33.3	0:06	14.5	103	20,700	55	210	50.7	
		3	1.000	0.665	33.5	0:12	14.5	115	20,700	56	250	51.6	
		4	0.665	0.440	33.8	0:09	14.5	120	19,800	56	270	47.0	
		5	0.440	0.291	33.9	0:13	14.5	125	19,800	56	278	49.3	
		6	0.291	0.195	33.0	0:16	14.5	128	18,900	57	351	48.1	
		7	0.195	0.125	35.9	0:18	14.5	129	18,900	57	412	48.6	
Losses during Rolling								In Kcal		In KWH	In %		
Heat Transfer to Strip								7,02,651		817.04	56.5		
Heat Transfer to Coolant								40,114		46.64	3.2		
Heat Transfer to Coolant Volume Loss								1,463		1.70	0.1		
Other Conduction Losses								4,99,817		581.18	40.2		
COIL -3 Data													
3	765	Coil Temperature before Rolling							30				
		1	2.000	1.500	25.0	0:07	14.5	46.2	20,700	56	218	50.8	
		2	1.500	1.000	33.3	0:08	14.5	105	20,700	56	217	52.6	
		3	1.000	0.663	33.7	0:13	14.5	116.5	19,800	56	243	54.0	
		4	0.663	0.440	33.6	0:11	14.5	122	18,900	56	271	54.3	
		5	0.440	0.293	33.4	0:12	14.5	125	18,000	56	311	53.6	
		6	0.293	0.182	37.9	0:14	14.5	128.9	18,000	57	355	54.7	
		7	0.182	0.117	35.7	0:18	14.5	131	17,100	57	492	55.0	
Losses during Rolling								In Kcal		In KWH	In %		
Heat Transfer to Strip								6,45,967		751.12	49.2		
Heat Transfer to Coolant								19,029		22.13	1.4		
Heat Transfer to Coolant Volume Loss								1,463		1.70	0.1		
Other Conduction Losses								6,46,599		751.86	49.2		

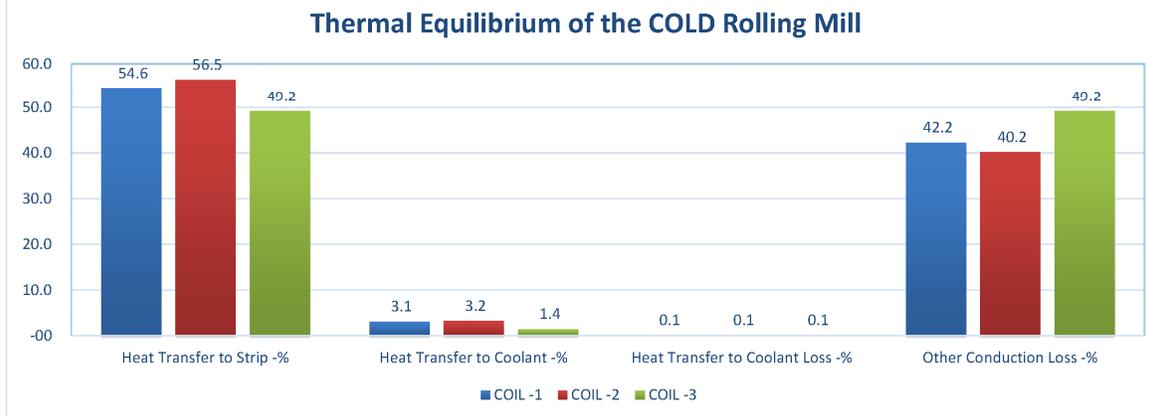


Figure 10. Sample Data from 6HI CRM 1250 mm x 1200 mpm

Coil Rolling Data - 6HI-CRM, 1300mm Wide @ 550MPM													
Sr No	Strip Width (mm)	Pass Number	Entry Thickness (mm)	Exit Thickness (mm)	Reduction (%)	Pass Time (Hour:min)	Rolled Tonnage	Strip Temp (Deg)	Coolant Level (Litre)	Coolant Temp (Deg)	KWH Consumed (KWH)	Workroll Temp	
Coil -1 Data													
1	1305	Coil Temperature before Rolling							35				
		1	2.150	1.600	25.6	0:12	25.84	60	28,960	58	200	54	
		2	1.600	1.230	23.1	0:10	25.84	77	28,508	56	240	56	
		3	1.230	0.930	24.4	0:10	25.84	99	27,874	59	256	53	
		4	0.930	0.690	25.8	0:13	25.84	102	27,150	59	320	58	
		5	0.690	0.500	27.5	0:15	25.84	105	26,517	59	354	58	
		6	0.500	0.360	28.0	0:18	25.84	113	25,702	59	420	56	
Losses during Rolling								In Kcal		In KWH	In %		
Heat Transfer to Strip								8,58,683		998.47	72.5		
Heat Transfer to Coolant								27,452		31.92	2.3		
Heat Transfer to Coolant Volume Loss								1,766		2.05	0.1		
Other Conduction Losses								2,96,253		344.48	25.0		
COIL -2 Data													
2	1305	Coil Temperature before Rolling							35				
		1	2.150	1.570	27.0	00:15	25.65	60	30,770	58	209	58	
		2	1.570	1.190	24.2	00:14	25.65	77	30,227	57	238	60	
		3	1.190	0.880	26.1	00:10	25.65	99	29,503	59	268	57	
		4	0.880	0.630	28.4	00:11	25.65	102	28,960	59	390	58	
		5	0.630	0.445	29.4	00:14	25.65	107	28,236	60	410	57	
		6	0.445	0.310	30.3	00:17	25.65	111	27,331	61	441	57	
Losses during Rolling								In Kcal		In KWH	In %		
Heat Transfer to Strip								7,70,133		895.50	61.8		
Heat Transfer to Coolant								87,514		101.76	7.0		
Heat Transfer to Coolant Volume Loss								1,864		2.17	0.1		
Other Conduction Losses								3,86,534		449.46	31.0		
COIL -3 Data													
3	1305	Coil Temperature before Rolling							35				
		1	2.150	1.570	27.0	0:13	25.7	58	27,150	59	224	58	
		2	1.570	1.190	24.2	0:11	25.7	79	26,426	59	250	56	
		3	1.190	0.880	26.1	0:12	25.7	89	25,702	58	291	57	
		4	0.880	0.630	28.4	0:14	25.7	99	24,978	59	349	58	
		5	0.630	0.445	29.4	0:18	25.7	101	24,254	60	398	62	
		6	0.445	0.310	30.3	0:20	25.7	113	23,530	61	477	65	
Losses during Rolling								In Kcal		In KWH	In %		
Heat Transfer to Strip								7,91,941		920.86	62.5		
Heat Transfer to Coolant								50,680		58.93	4.0		
Heat Transfer to Coolant Volume Loss								1,962		2.28	0.2		
Other Conduction Losses								4,22,484		491.26	33.3		

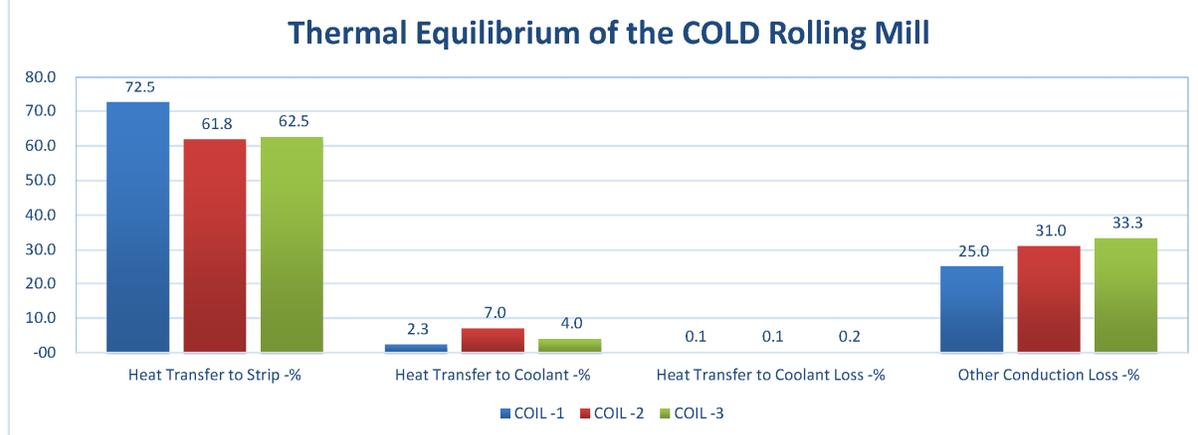


Figure 11. Sample Data from 6HI CRM 1300 mm x 550 mpm

Table II. Mill Energy Distribution

Mill Specifications	Energy Distribution (%)			
	Coolant	Evaporation	Strip	Body mass and other losses
6HI-CRM, 1250 mm @ 800 MPM	8%	0.1%	80%	12%
6HI-CRM, 1250 mm @ 1200 MPM	3%	0.1%	55%	42%
6HI-CRM, 1300 mm @ 550 MPM	4%	0.2%	63%	33%

It is to be noted that more number of passes result in higher yield stresses in the strip and greater conduction occurs between the strip and the rolls. Hence, the energy going in to the strip is less than the reduction energy and half the friction energy³.

As the strip thickness becomes smaller, the flattening of the rolls and the axial bending of the rolls become proportionally larger. At some stage, depending on the roll force, the strip width, roll crown and roll bending force, the top and bottom work rolls will come in contact outside the strip edges⁴.

A higher roll force has a tendency to make the strip shape poorer but the edge contact force in the work rolls plays an important role in the thin strip rolling process. If the edge contact force between the two work rolls is controlled between 11 to 15 percent, it can improve the strip shape⁵.

During roll flattening the force applied to the strip will approach a fixed ratio of the total roll separating force and can be controlled to improve the strip profile.

CONCLUSION

The unique roll profile in the YOGIJI-DIGI reversing cold rolling mills has led to:

1. 12 - 15 % more reduction on the strip and hence lesser number of passes.
2. Reduced number of passes means lesser yield stresses on the strip.
3. Better strip shape profile on account of controlled work roll edge contact force.
4. Reduced thermal and mechanical fatigue on the rolls.
5. Elimination of cooling arrangement for emulsion system.
6. 2 - 3 % reduction in the rolling power consumption.
7. 356 tons of CO₂ emissions saved every year.

ACKNOWLEDGEMENTS

The authors would like to thank Prompt Enterprises, Haryana, India, Aarti Rolling Mills Ltd., Ogun State, Nigeria, Aarti Steel PLC., Ethiopia for providing data from their respective 6HI Cold Rolling Mill's which has been used in this research paper.

REFERENCES

1. William L. Roberts, "Thermal Aspects of the Cold Rolling Process", *Cold Rolling of Steel*, Marcel Dekker Inc., New York, USA, pp 332-398
2. Daron Lloyd, MD Lechler Ltd., "Fundamentals of Roll Cooling and Control of Flatness at Primary Cold Reduction", Workshop on Cold Rolling Technology, Thane, India, March 2012
3. Domanti, S.A., Edwards, W.J. and Thomas, P.J., "Design of Rolling Mill Strip and Roll Cooling Systems", AISTech 2004
4. Domanti, S.A., Edwards, W.J. and Thomas, P.J., "A Model for Foil and Thin Strip Rolling", AISE Annual Conference 1994
5. Jiang, Z.Y., "Mechanics of Cold Rolling of Thin Strip", Workshop on Cold Rolling Technology, Thane, India, March 2012