HORNS OF HEAT – WORK ROLL COOLING DISTORTIONS [1]

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Abstract

It has been 10 years since the original paper on roll cooling distortions was made, and they have been proven valid by actual trials on hot strip mills. It is sad to say too many technical papers show symmetrical convex thermal crowns, which is a rarity in the "real" world. Many hot strip mill operators refuse to believe this concept. One mill with a thermal crown model shows the concave thermal crowns with "horns of heat" near the edges, which exactly matched the author's thermal crown model. The operators refused to believe their computer model or the author's thermal crown projections, and still operate the mill the with the same shape problems.

Keywords: Thermal crowns; Roll cooling; Heat balance; Roll temperatures.

Resumo

Já se passaram 10 anos desde os conceitos dos problemas de refrigeração de cilindros foi publicado e estes se comprovaram atuais de acordo com as últimas experiências realizadas em LTQ's. É triste dizer que nestes últimos anos, muitos trabalhos técnicos foram publicados, mostrando coroas térmicas convexas e simétricas, o que é uma raridade no mundo real. Muitos operadores de LTQs recusam-se a acreditar o que se discute neste trabalho. Um LTQ com modelo de coroa térmica mostrou coroa térmica côncova com "chifres de expanção térmica" próximos as bordas, coincide exatamente com o modelo térmico deste autor. Os operadores recusam-se a acreditar nos seus modelos térmicos, e continuam operando seus laminadores com os mesmo problemas de planicidade.

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A. Thermal Crowns

Very few people have had an opportunity to work on over 100 hot strip and cold strip mills. Working on shape and roll cooling problems since the 1960's provided an opportunity to record work roll temperatures (thermal crowns) under many different circumstances. The left side on each graph is the operating side the work roll. The temperature (vertical axis) is either in ºF or ºC depending on the original data.

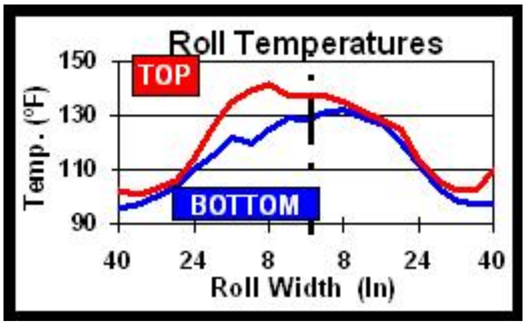


Figure 1a – Hot Strip Mill [1]

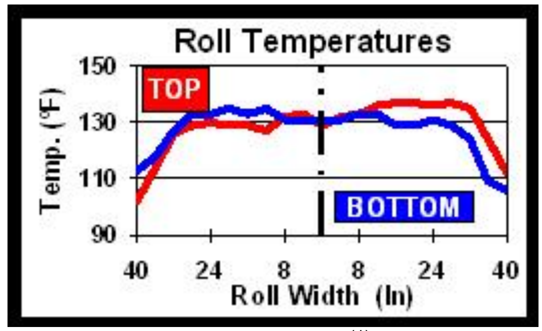


Figure 1b – Hot Strip Mill[1]

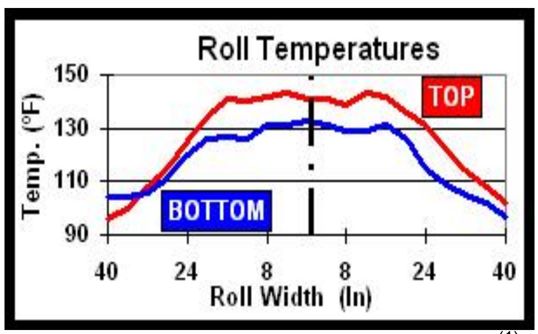


Figure 1c – Hot Strip Mill [1]

The work roll temperatures above are from a hot strip mill. Figure 1a has uneven, convex, tapered, and batwing shaped thermal crowns. Figure 1b has concave with shoulders and uneven thermal crowns. Figure 1c has uneven, flat, and tapered thermal crowns.

Figure 2 below shows work roll temperatures from a cold strip mill where the thermal crowns on #1 mill are concave, uneven, tapered and have batwings, #2 mill has one roll with an uneven, flat, and batwing thermal crown while the other roll has an uneven, convex, and batwing thermal crown. #3 mill has uneven, concave, and batwing thermal crowns.

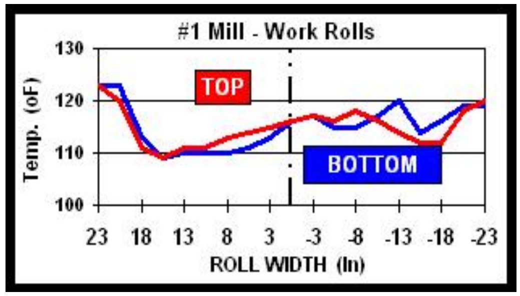
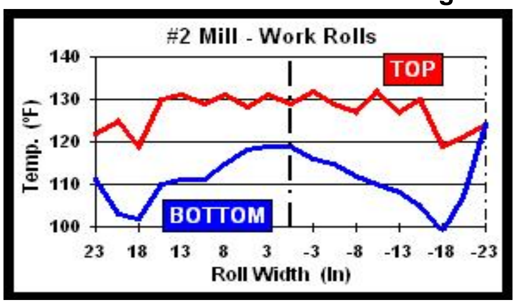


Figure 2a – Cold Strip Mill



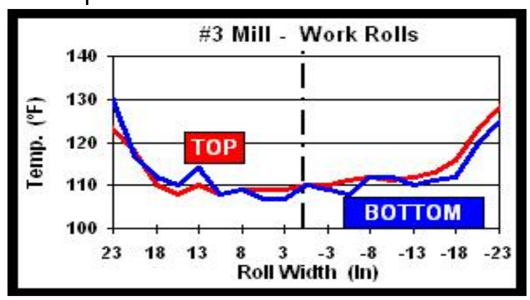
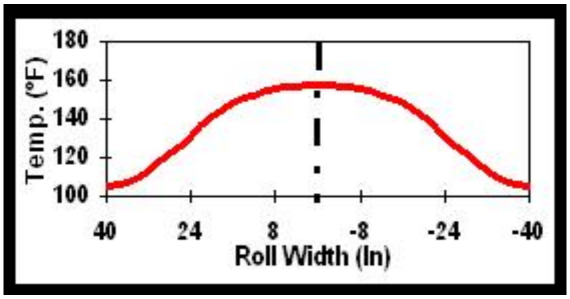


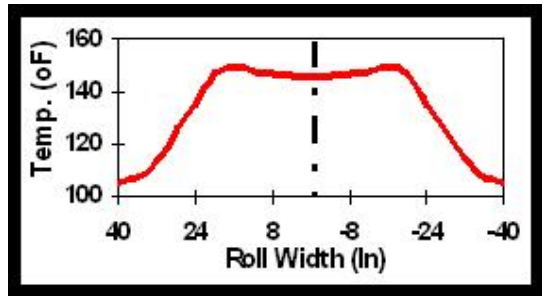
Figure 2b – Cold Strip Mill **Figure 2c –** Cold Strip Mill

The maximum work roll temperature is **not the important part**; the important aspect is the temperature profile (**thermal crown)** across the width of the work roll, and its relationship to the bending characteristics of the work and backup rolls. During these years many peculiar and odd shaped thermal profiles were seen. Some other times they were taken intermediately after roll changes, rolls changed for a broken roll, or changed for firecracks, bruises, or roll marks, etc. At first, these strange thermal profiles were attributed to plugged nozzles, poor header fabrication, or poor maintenance. In many cases, the cooling headers were inspected, but often no evidence was found to support maintenance problems caused of these unusual thermal crowns.

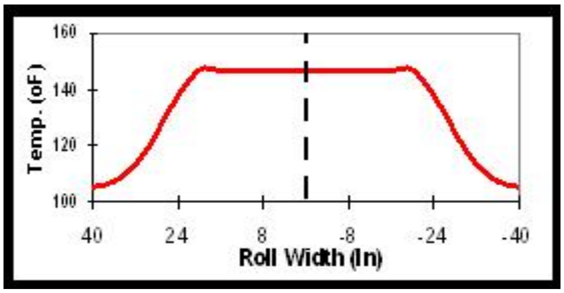
The most unusual thermal crowns seem to occur on when rolling wide schedules, more often when rolling light gage, and on mills using non-uniform roll cooling designs. Spending a lot of time on the mill floor it is possible to see shape changes out of each mill stand. Slowly some thermal crown and shape patterns began to be recognized. Some mills had certain characteristics, such as wavy edges out of F4 mill and using different mechanical crowns did not eliminate this pattern. One cold mill produced a center buckle with short choppy edge waves, and changing the amount of mechanical crown or center cooling did not help. Another hot strip mill would have a light wavy edge on one edge, and if the mill were leveled the strip would camber. A number of these mills had quarter line buckles, feathered or wavy edges, and duplex shape problems. The major complaint by mill operators was the mill became **unstable, inconsistent,** or **uncontrollable** when rolling wide strip.



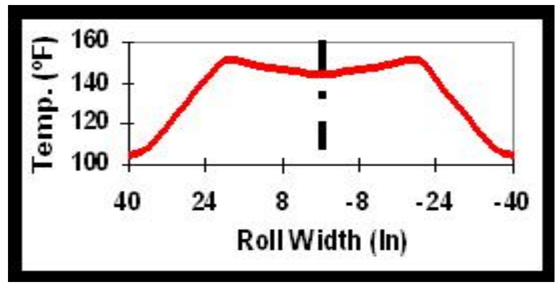
3a - Convex



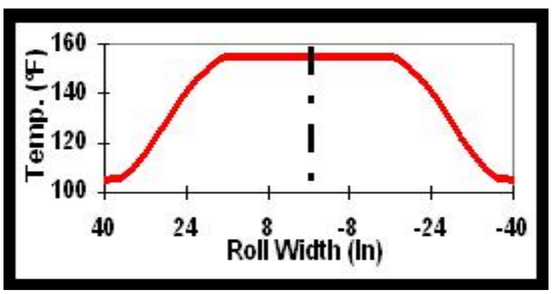
3b - Concave



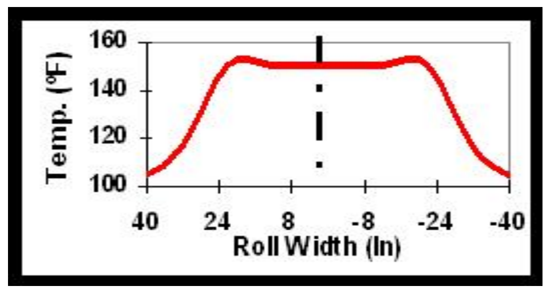
3c – Flat



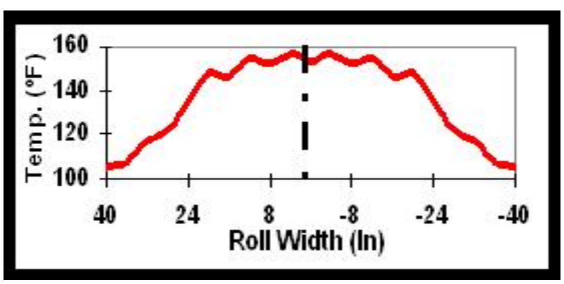
3d – Concave with Shoulders



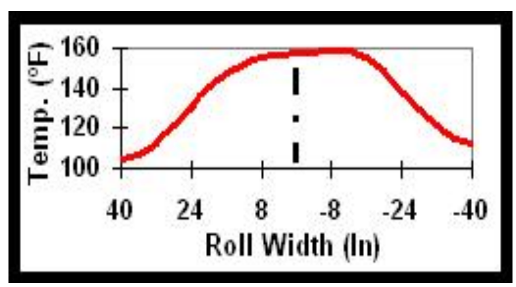
3e – Flat



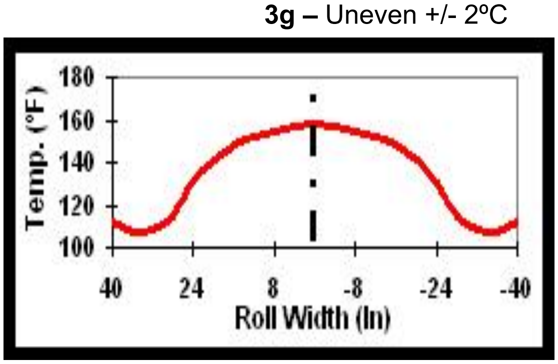
3f – Flat with Shoulders



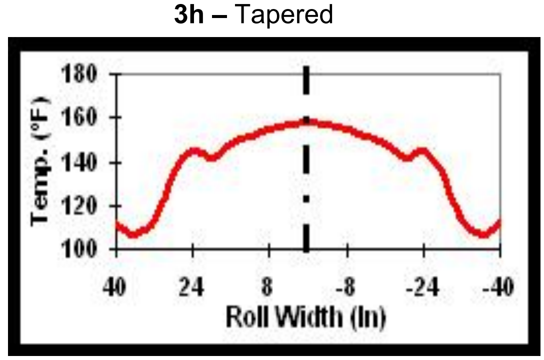
3g – Uneven +/- 2ºC



3h – Tapered



3i – Batwings



3j - Combinations

Different types of thermal crowns are shown in Figures 3a to 3j.[3] There can be combinations of these types of thermal crowns. For example, in Figure 3j the profile has **CONVEX**, **SHOULDERS** and **BAT WINGS** as shown. It was hard to believe.
These thermal crowns could exist, and Figures 4 and 5 are even more interesting.[1] These thermal crowns were taken on the same work roll at different times during the rolling one wide rolling schedule. After the mill began rolling the mill was periodically stopped, the work rolls were removed, the roll temperatures taken, the work rolls replaced; and the rolling continued until the next temperature test was repeated.

B. Actual Thermal Crowns

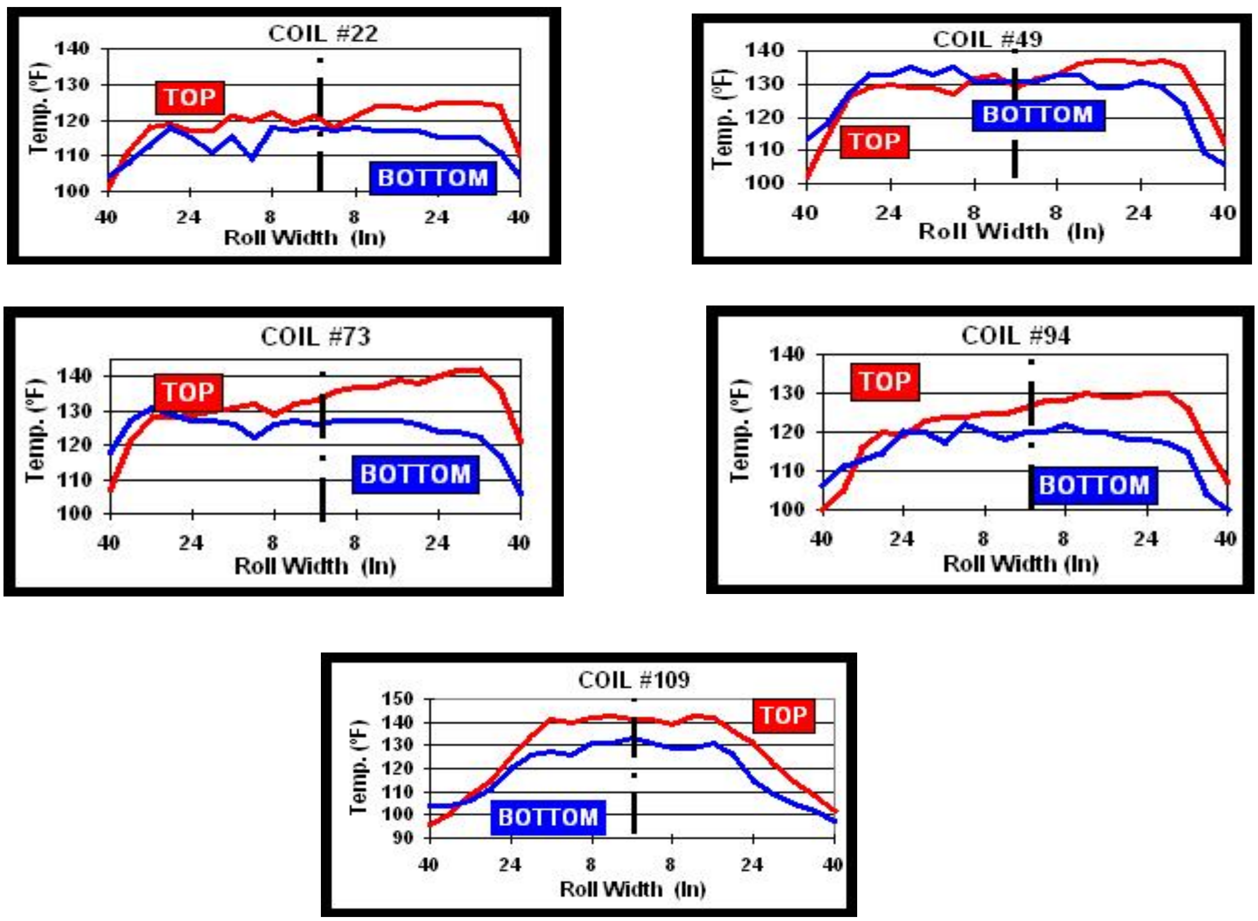


Figure 4 – Thermal Crowns [1]

Figure 4 are thermal crowns from a mill rolling large slabs taken after rolling coils #22, #49, #73, #94 and #109. This wide schedule produced thermal crowns ranging from tapered to flat to concave, and all had shoulders and uneven profiles. Not one of the thermal crowns was convex or symmetrical, but the last coil (#109) began to move in that direction. This is an example of a roll cooling design with **center section cooling**, and the nozzle's offset angles aligned in the same direction.

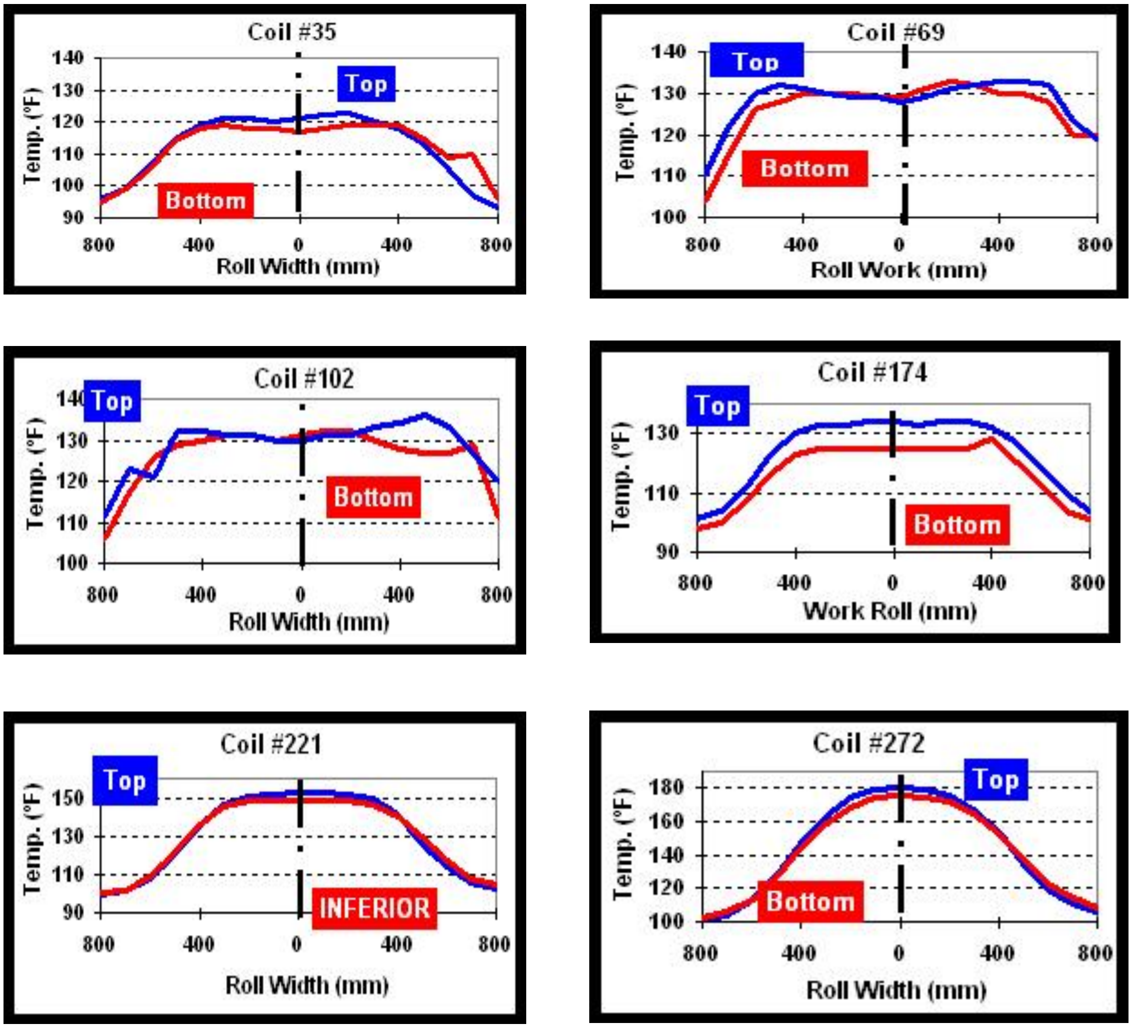


Figure 5 - Thermal Crowns [1]

In Figure 5, the thermal crowns were on a mill rolling small slabs with temperatures taken after bobinas (coils) #35, #69, #102, #174, #221, and #272. The roll cooling headers were extremely well maintained. The various thermal crowns range from flat to concave with shoulders, some taper, but finally to an almost perfect convex thermal crown. This is an example of a tapered roll cooling design when rolling a "coffin" shaped schedule, but with many wide coils of the same width rolled.

When the thermal crown data was reviewed, most mill operators could not believe such changes could occur during a rolling schedule. **"NOT on my HOT (COLD) STRIP MILL!"** These variations are not the exception. **These are typical of those found on most hot strip and cold strip mills.** How is it possible to for these odd and inconsistent thermal crowns to be created? The mill operators on hot and cold strip mills: **[a]** were provided with, **[b]** requested, or **[c]** developed their own roll cooling design create these thermal crowns. Look at the thermal crowns in Figures 1 to 5 in relation to shape and rolling problems. Could any mill roll good shape with these thermal crowns? More seriously, could the million dollar shape control systems (bending, shifting, cross angle, CVC. etc.) improve the strip shape with these thermal crowns? **The ANSWER is NO!!!**

C. Heat Balance

How do these thermal crowns occur? What is the underlying cause? Why does the thermal crown change within a rolling schedule from convex, to flat, to shoulders, to concave with shoulders, to flat with shoulders, and back to convex at the end of the rolling schedule? The answer lies in the "heat balance" between the roll cooling design **(heat removal)** and the rolling schedule by coil width **(heat input)**. The work roll cooling arrangement and volume distribution is the **direct heat removal** pattern. The roll cooling offset angle influences the **indirect heat removal**. The work roll length and strip width influences the work roll's **heat removal** by conductivity to the roll ends. The various coil widths in a rolling schedule sets the **heat input** pattern across the roll. The rolling pace, i.e. the percent of time a strip is in the mill greatly influences the **amount of heat input** and **heat removal** required.

It is the balance of the **heat input** and **heat removal**, which determines the eventual thermal crown. First, there is a difference between the **thermal crown** and **work roll temperature.** The **thermal crown** is the average temperature of the work roll. The **work roll temperature** is only the work roll's surface temperature. For example, the surface temperature can be 60ºC (140ºF) after rolling 10 coils, but the average work roll temperature (thermal crown) may only be 40ºC (105ºF). The thermal crown is lower than the work roll surface temperature when rolling first begins as the heat is conducted into the cold interior of the work roll. After the roll temperature has stabilized, the thermal crown is lower or higher than the work roll surface temperature whenever the rolling pace decreases or increases. In this paper, the term **thermal crown** represents the average temperature of the work roll.

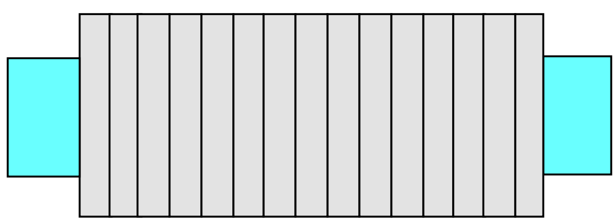


Figure 6 – Roll Segments [3]

Figure 6 shows a work roll in 100mm segments used to calculate the **heat balance** without considering conductivity of heat to the ends or between the segments. Each isolated roll segment shows the **heat balance** between the **heat input** (coil width) and **heat removal** (roll cooling design) for that segment across the work roll.

A wide "coffin" rolling schedule is shown in Figure 7 starting at 915mm, widens out to 1825mm, and narrows down to 1050mm. The final length of strip rolled is 100Km. Figure 8 is the roll cooling distribution used rolling this schedule. More roll cooling is concentrated in the center of the work roll by using larger nozzles toward the center of the roll. There was very little cooling near the roll ends.

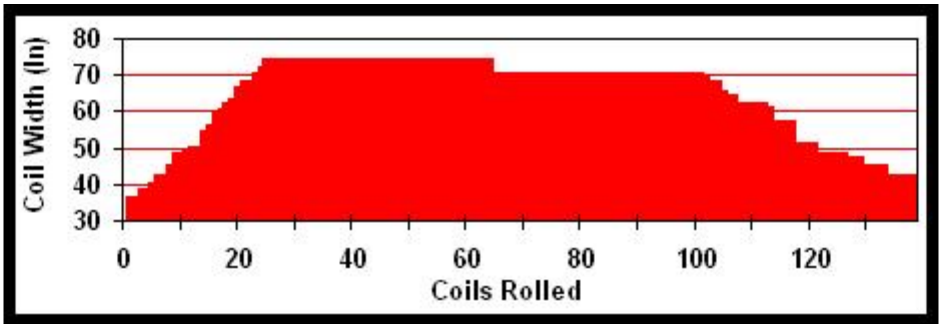


Figure 7 – Rolling Schedule by Coil Width [(1)]

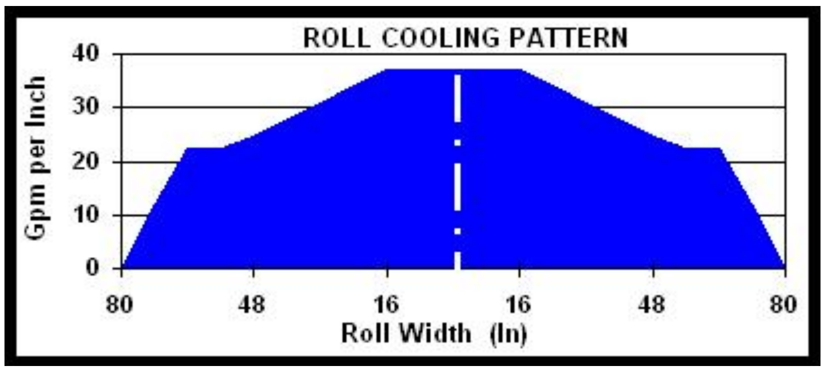


Figure 8 – Roll Cooling Distribution across the Roll [(1)]

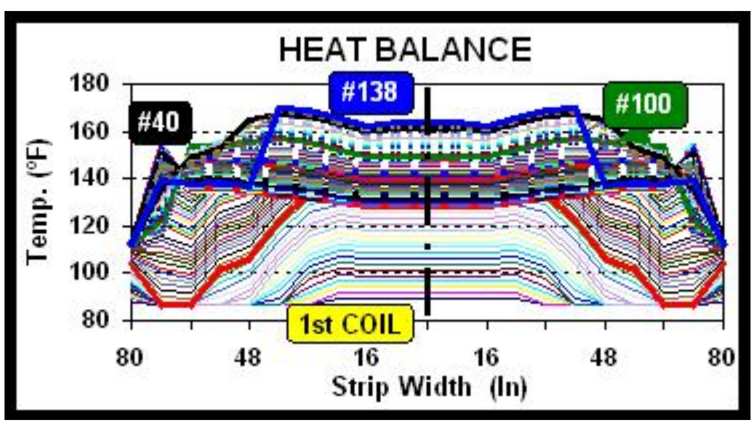


Figure 9 – Heat Balance in 4" Segments [(2)]

Figure 9 is the **heat balance** created in each 100mm segment rolling this schedule with this roll cooling design. The thermal crown increases for about 25 to 35 coils, and then stabilizes. Thereafter, the thermal crown increases or decreases depending the change in the rolling pace. As can be seen here, the **heat balance** near the roll ends results in

what is called "**horns of heat".** This confines the heat in the center of the roll, and creates many unusual thermal crowns.
A wide rolling schedule was selected to illustrate **work roll cooling distortions** caused by roll cooling designs. The rolling pace is high at the beginning rolling narrower coils, drops to a slower pace rolling wide coils due to the furnace capacity, and increases toward the end of rolling schedule rolling narrow coils as shown in Figure 10. The thermal crown is lower than the work roll surface temperature at the beginning of the schedule, becomes about the same after the roll temperature and rolling pace stabilizes in the middle part of the schedule; and is higher as the rolling pace increases toward the end of the schedule rolling narrower coils.

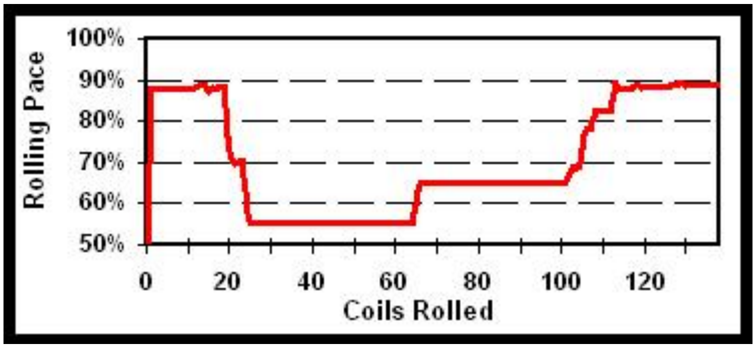


Figure 10 – Rolling Pace = % Contact Time

D. Projected Thermal Crowns

The rolling schedule shown in Figure 7 is used to calculate the thermal crowns using four different roll cooling designs shown below with the same cooling volume.

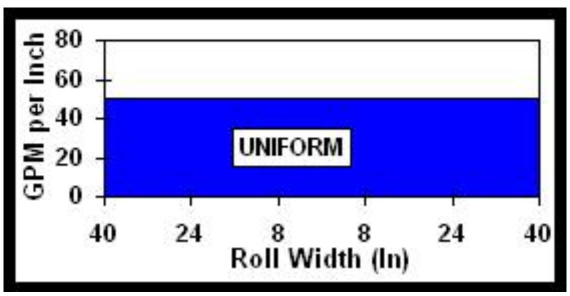


Figure 11a – Uniform Cooling

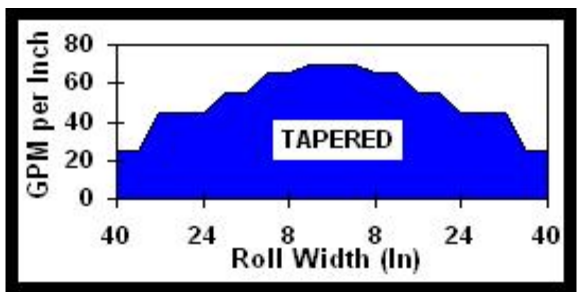


Figure 11b – Sectional Cooling

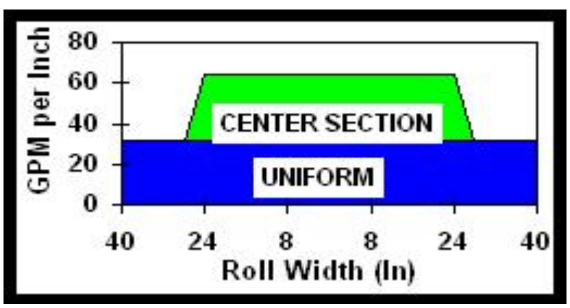


Figure 11c – Tapered Cooling

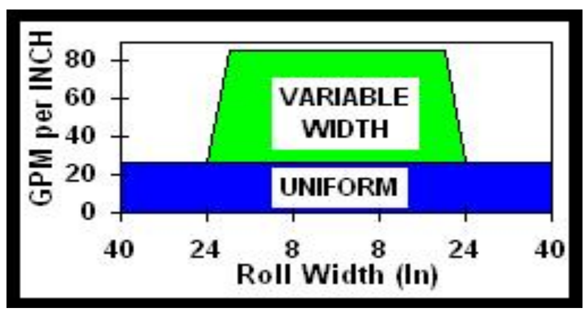


Figure 11d – Variable Cooling

The vertical axis is the cooling volume in GPM per inch of roll width, and the horizontal axis is the cooling width for each design. With **tapered** cooling the water volume increases toward the center by using larger nozzles or closer nozzle spacing. **Variable** cooling applies uniform cooling on one side of the work roll, and on the other side the cooling is as wide as the strip width being rolled. This would result in the variable cooling width following the coil widths seen in Graph 7. The roll cooling volume is the same for each cooling design to compare the work roll temperatures.

The thermal crowns shown in Figures 13a, b, c, and d are the roll cooling model projections after coils #20, #40, #60, etc. with other factors of rolling pace, coil width, slab size, etc. held constant on this rolling schedule.

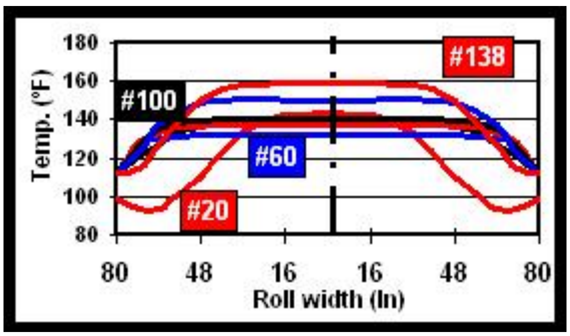


Figure 13a – Uniform Roll Cooling (2)

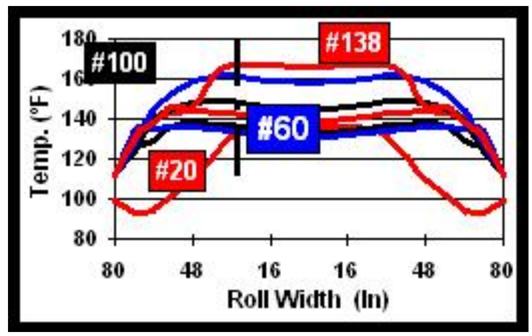


Figure 13b – Center Section Cooling (2)

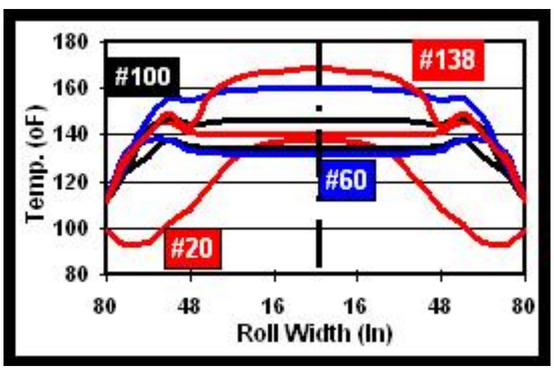


Figure 13c – Tapered Cooling (2)

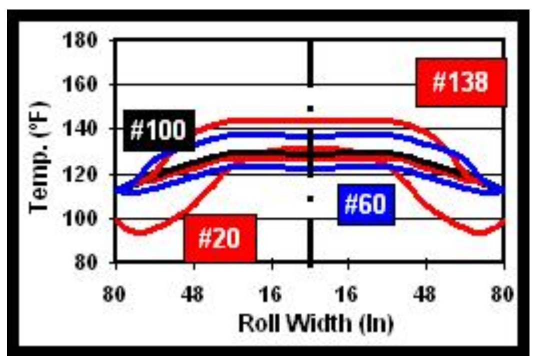


Figure 13d – Variable Width Cooling (2)

The **uniform cooling (13a)** thermal crowns starts with a convex shape on #20 coil, but becomes flat in the center with shoulders inside of the coil width on coils #40, #60, #80 and #100 after rolling many coils of the same width. By coil #120 where the coil width is narrower the crown is becoming convex, and after the last coil (#138) rolled the thermal crown is convex. This phenomenon of the center of the thermal crown going "flat with shoulders" is of great importance on cold mills because they often roll many coils of the same width. **Uniform cooling (13a)** results in the highest work roll temperatures occurring on narrow schedules, but lower than with **center section** or **tapered cooling** designs when rolling wide schedules. These thermal crowns result in light quarter line buckles and feathered edges on wide schedules, and a flat strip profile when finishing rolling narrow coils.

The **center section cooling (13b)** thermal crowns when rolling coils wider than the **center section cooling** increases the work roll center temperature to be equal or higher than with **uniform cooling**. The thermal crown on coil #20 is convex, but becomes flat with high shoulders on coils #40, #60, #80 and #100. When coil #120 is the rolled and the coil width is narrower, the shoulders become smaller with the thermal crown becoming convex. The thermal crown after coil #138 is convex, which is typical of thermal crowns taken at the end of a rolling schedule. **It is assumed by most mill operators the thermal crown is convex for the entire schedule.** The center roll temperature will be higher than with any other design, and results in a flat or negative strip profile on narrow coils towards the end of the rolling schedule.

Rolling coils narrower than the **center section cooling** width results in the center roll temperature being lower than with a **uniform cooling** design. Using **center section cooling** is the poorest roll cooling design for shape on wide schedules, unless the extra center cooling is shut off when rolling wider strip. If the center headers are shut off, the thermal crown will become hotter than with uniform cooling because 30% to 50% of the cooling volume is shut off. **Center section cooling** headers are the direct cause of severe quarter line buckles and feathered edges produced on both hot and cold strip mills. It also causes short choppy edge waves and duplex shape.

Tapered cooling (13c) applies more water in the center of the work roll in an attempt to get around the **center section cooling** characteristics. This helps modify the abrupt changes in the thermal crown across the roll width. The thermal crown on #20 coil is convex, but quickly goes concave with shoulders and stays there on the remaining coils in the schedule. The shoulders are not as abrupt as with **center section cooling**, and results in less severe quarter line buckles and feathered edges. The water distribution can be changed to improve this, but then other rolling schedules will have poorer thermal crowns. This design is better than using **center section cooling**, but only to a small degree.

The **variable width cooling (13d)** thermal crowns combines the best parts of the **uniform, center section** and **taper roll cooling** designs. This increases the cooling capacity by having water being concentrated at the strip width compared to **uniform cooling**. The **variable width cooling** header is installed on the exit side on hot strip mills, but on the entry side in cold mills. The results shown in Figure 13d are: **[a]** a convex thermal crown from beginning to the end of the schedule regardless of the coil width, and **[b]** the lowest work roll temperatures, but tends toward a flat thermal crown when many coils of the same width are rolled.

It is this tendency for the thermal crown to go "flat" using any roll cooling design, which causes featheredges, and why hot strip mills limit the number of coils rolled of within 25mm of the same width. **Variable width cooling** has the least tendency to form a flat thermal crown, and can be corrected by modifying the cooling width.

Most operators are concerned with the maximum work roll temperatures. When rolling wide and narrows schedules reach the maximum work roll temperatures shown in Figure 14 with these four roll cooling designs. Rolling a wide schedule using **uniform cooling** the work roll reaches 158ºF (70ºC), with **sectional cooling** it is 165ºF (74ºC), with **tapered cooling** it is 166ºF (74ºC), and with **variable width cooling** it is the lowest at 147ºF (64ºC). Rolling a narrow schedule increases the work roll temperatures due to a higher rolling pace to 185ºF, 178ºF, 176ºF, and 168ºF, (85ºC, 81ºC, 80ºC, and 75ºC) respectively for **uniform, center section, tapered,** and **variable width cooling**.

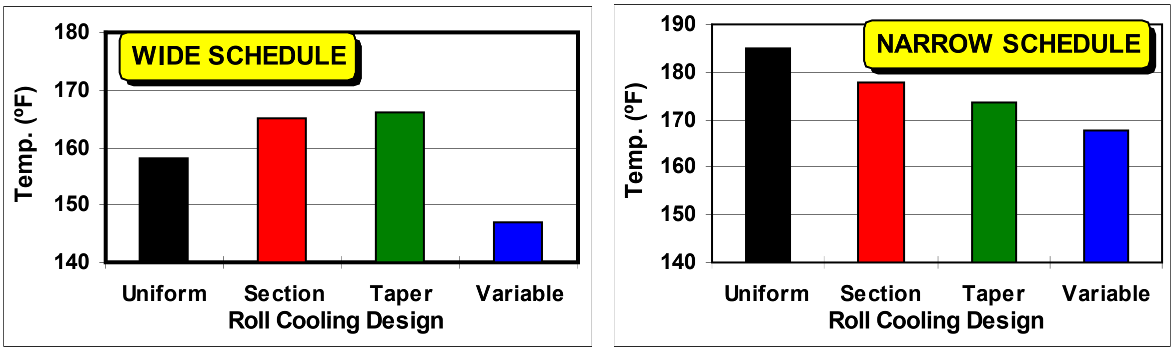


Figure 14 – Maximum Work Roll Temperature [3]

Work roll temperatures have little to do with hot strip and cold strip mill shape or rolling problems. **The important part is the symmetry and uniformity of the thermal crown in each mill stand.** The **work roll cooling distortions** caused by the roll cooling design leads to poor shape and strip profiles and rolling problems.

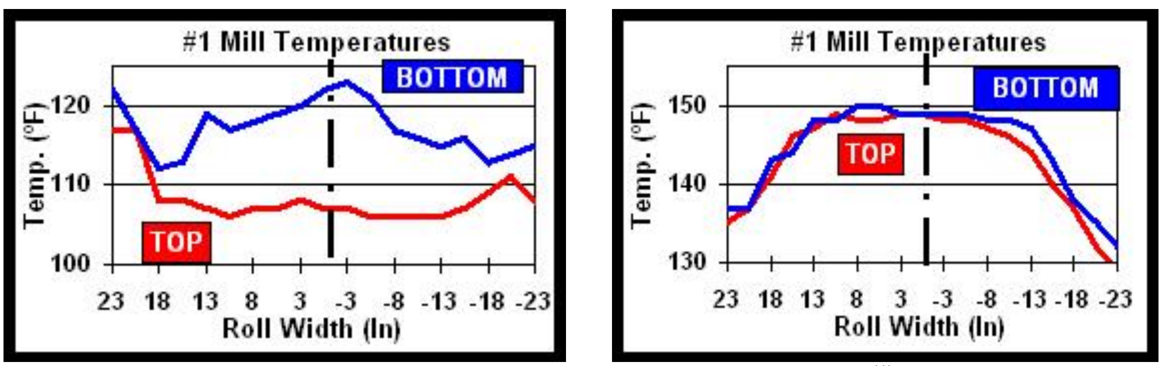


Figure 15 – Thermal Crowns – Before and After [1]

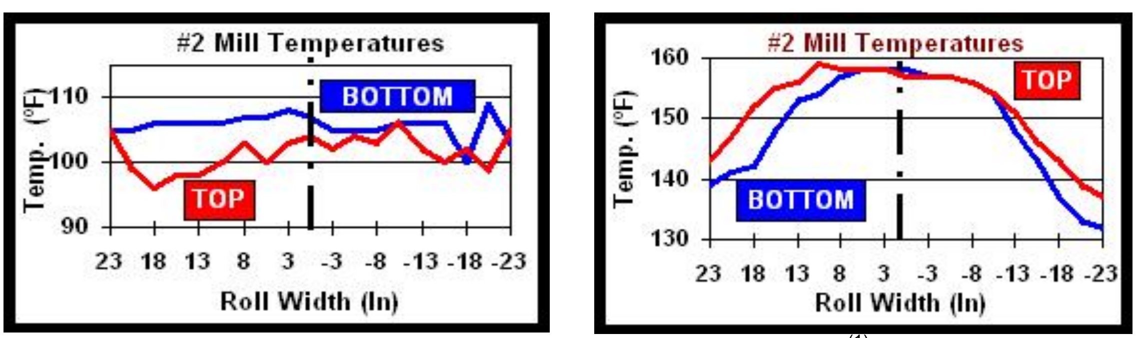


Figure 16 – Thermal Crowns – Before and After [1]

Figures 15 and 16 illustrate a cold mill plagued by shape and rolling problems was forced to roll at low speeds with the original roll cooling design to minimize rolling problems resulted in low work roll temperatures and low productivity. The two graphs are the **before** (left) and **after** (right) modifications were made on #1 and #2 mills. The roll cooling design was modified by: **[a]** extending the cooling width, **b]** changing nozzles, and **[c]** changing the offset angles for better cooling. New headers with the nozzles offset from the center would eliminate the **taper** and **uneven** variations in these thermal crowns. The results of modifying the roll cooling design resulted better shape, higher work roll temperatures, and increased production because the mill could now roll faster.

Work roll thermal crown distortions are caused by **[a]** poor roll cooling design, **[b]** improper offset angles, and **[c]** maintenance due to plugged sprays, damaged sprays, or missing sprays. The last two items are within the control of the operators, but the first item **[a]** is the major problem result from using the "accepted technology" on roll cooling designs creating a fixed pattern of cooling using **uniform, center section,** or **tapered** designs.

Rolling schedules of different width coils very seldom result in **convex** thermal crowns. When nonuniform thermal crowns occur, no amount of changing roll crowns, changing rolling solution, or mechanical shape control systems will correct the shape problem. In fact, almost all of the roll cooling designs are the basic cause of "sub-standard performance" of the roll bending, cross rolling, CVC, etc. shape control systems on many mills.

Summary and Conclusions

- The concept of lower work roll temperatures using center section or tapered cooling only applies when the entire schedule rolls coils narrower than the extra cooling in the center of the work roll.
- Center section and tapered roll cooling designs are the basic cause of: **[a]** quarter line buckles, **[b]** feathered edges, **[c]** duplex shape, **[d]** short choppy wavy edges, and **[e]** flat or concave strip profiles at the end of a rolling schedule.
- Any roll cooling design (uniform, center section, or tapered), which is a fixed design results in different thermal crowns on every rolling schedule because the **HEAT INPUT** (coil width) in a rolling schedule constantly varies.
- The thermal crown taken at the end of a rolling schedule is not representative of the thermal crowns created during the rolling schedule, and assuming the final thermal crown represents the entire rolling schedule is a mistake.
- Operators look at the work roll temperatures and forget the thermal crown profile
- Failure to cool the entire width of the work roll results in batwing thermal crowns, and contributes to backup roll spalls and other rolling problems.

Much has been learned, but more work is required to understand the effects of roll cooling design on **distortion of the work roll thermal crowns.**

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