Resolving Complex Shape Distortions on Narrow, Thin-Gauge Strip Having an Asymmetric Transverse Thickness Profile — Case Study: Part 1 — Defining the Problem

Certain cold reduction operations involve rolling narrow, thin-gauge strip having an asymmetric transverse thickness profile, formed from wider, symmetric profiled material being slit along the longitudinal axis. This material compromises the mill's shape actuation capabilities. Rolling this material may expose deficiencies in the mill that are not evident when rolling wider, symmetric material. This article is the first in a two-part case study that defines/examines this complex and confounding rolling scenario.

This article is the fifth in a series by Mark E. Zipf. The preceding parts were published in sequence in the December 2012, February 2013, February 2014 and December 2014 issues of *Iron & Steel Technology*.

Multi-stage rolling involves a series of (possibly recursive) process stages. Each stage imparts a defined parametric transformation of the incoming coils (i.e., reduction, geometry, work hardening, surface quality, etc.) through scheduled multi-pass rolling and annealing thermal cycle profiles. Although certain "in-process" quality objectives and tolerances may be in effect, only the final/delivered coil quality and conditions are of absolute concern. Fig. 1 illustrates a classical 3-stage finishing process involving breakdown, intermediate and final rolling, and defines the key interstage constraints.

Although the term "breakdown" is used in the finishing sequence, this is just a designation for the heaviest finish rolling stage, since the "true" heavy-gauge breakdown rolling is performed upstream, by a typically larger, wider mill.

This type of multi-stage rolling is common in various materials, including stainless steels, copper/brass and specialty alloys.[1–4] While typical mill production throughput demands (tonnage) are present, the priority of the final stage component (finished rolling) is generally quality, because this will be the last reduction mill to touch and "work" (reduce) the high-value-added material (although skinpass or leveling treatments may be performed downstream).

As noted in Fig. 1, the finished coil has "fixed" specifications (associated with the planned/delivered product) and, thus, the incoming coils (post-intermediate rolling) will also have certain fixed specifications. Therefore, the only degrees of freedom in considering alternate rolling activities are in the intermix of breakdown and intermediate rolling, although there may be some available freedom in reconfiguring the specifications of the incoming coils (pre-breakdown) to assist in the 3-stage finishing activities.

This 3-stage finishing process can be carried out by three separate rolling mills or by a single mill operating in a recursive scenario. Regardless of the arrangement, the mill in each stage has to be configured/set up and scheduled to accommodate the material, rolling operation, and interstage objectives/constraints. In the recursive/single-mill arrangement, the mill must be operated in a pseudo-campaign format, where a series of "similar"/stage-designated coils will be rolled before converting to the setup and scheduling for the next designated stage of operation.

Upstream rolling operations that "feed" this multi-stage finishing process typically involve larger mills rolling wider, heavier gauge materials. Prior to entering this finishing process, the "master" coils are slit to form narrower strip. As shown in Fig. 2, the slit, narrowed material may take several forms having different transverse thickness profiles.

These profiles present some formidable complications. The asymmetric profiles require the roll gap to maintain a degree of transverse skew (matching the wedged strip profile) needed to form a cross-width uniform reduction/elongation (to preserve good shape). Wedged strip coil buildup will tend to form conical, cross-width coil diameter profiles and track/"dish" toward the thicker side. The transverse tension profile will likely be non-uniform, leading to planar shearing, diagonal stresses, herringbone and complex wrinkling. The shape measurement system must

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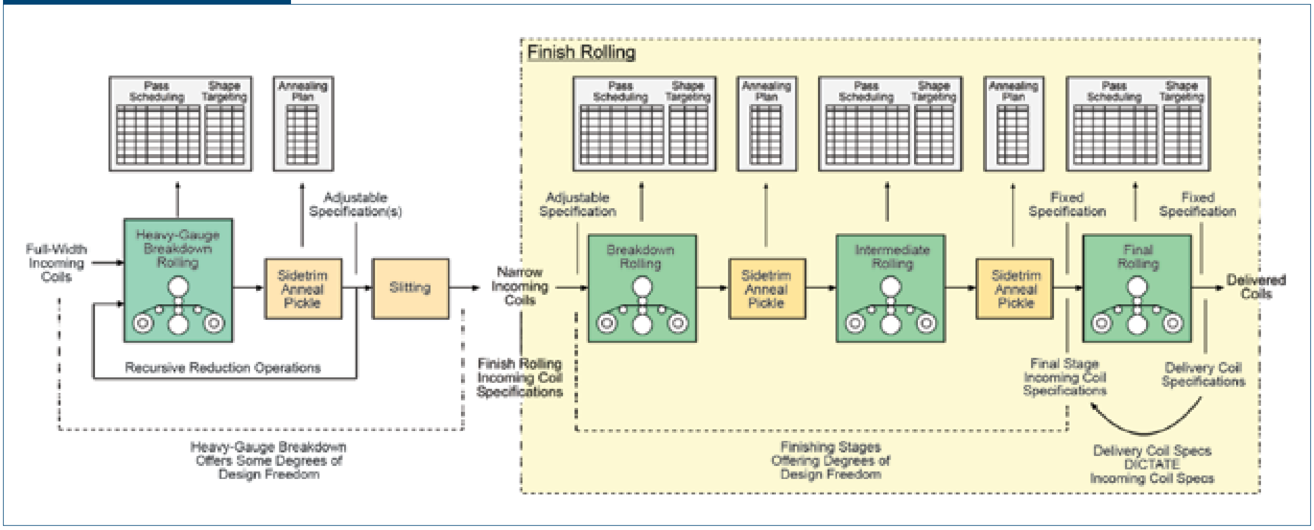
Figure 1

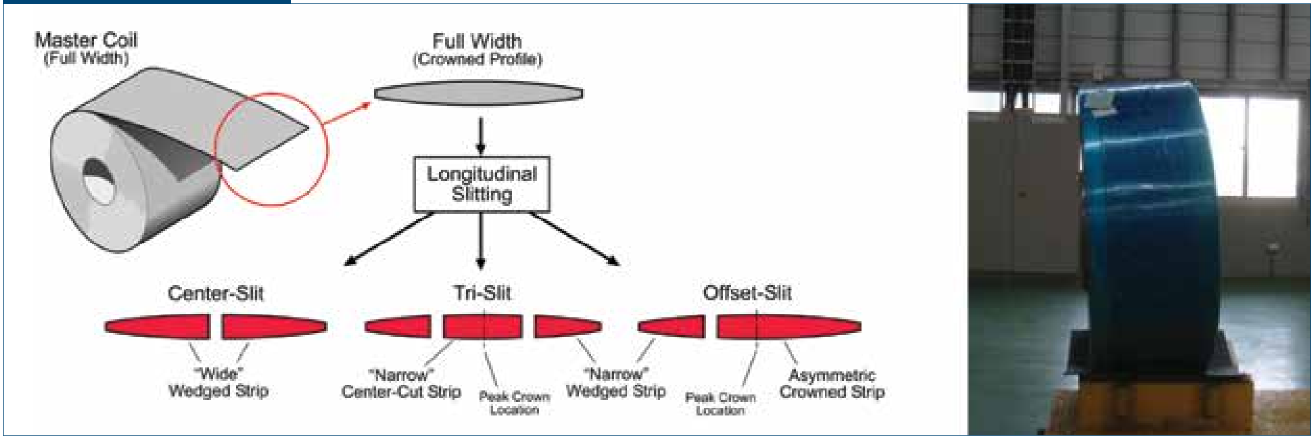


Block diagram showing a classical 3-stage cold rolling finishing process sequence.

understand the circumstances and provide the appropriate compensation, so as to not mislead the shape control activities with false readings. The offset asymmetric crown (Fig. 2) is perhaps the most difficult, primarily because the transverse resolution of the shape actuation (on the narrow strip) may be too "coarse" and not able to directly address the localized effects of the offset crown. This can result in narrow, sustained buckling distortions on one side of the strip centerline. The original, full-width edge region contours may be further compromised by edge drop.

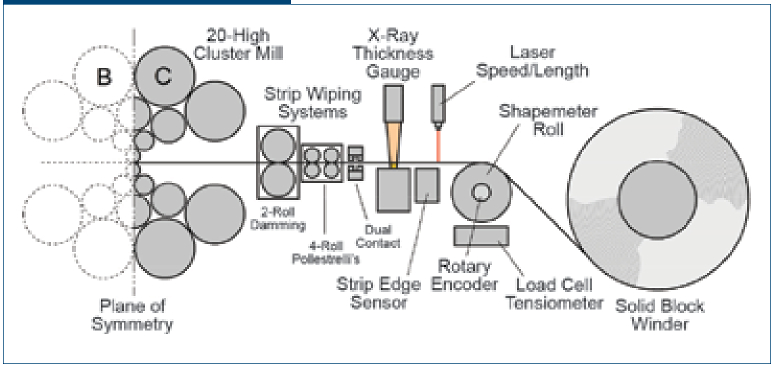
The final stage material can be exceedingly thin (down to 50 mm (0.002 inch) or lower), with high total reductions (exceeding 85%), having work-hardened yield stresses exceeding 1,400 MPa (200 ksi). Reducing this material may require a high number of passes (nine or more), and it's not uncommon for wider mills to experience "below face" rolling with top/bottom work roll contact outboard the strip edges. This causes the applied roll force to be transmitted around and not into the material, requiring tension or speed/friction-actuated automatic gauge control (AGC) methodologies. Coils of this thin strip will be very long (>50,000 m (9.5 miles)) and in-pass work roll wear can be a factor. Contact strip wiping (both roller and contact/rubbing) can be easily compromised, and the strip is highly sensitive to shape distortions and edge cracks. There are often critical surface quality specifications requiring the use of polished and/or superfinished work rolls on the last few passes.

Figure 2



Formation of slit/"narrowed" asymmetric profiled strip and resulting conic coil geometry.

Figure 3



Conceptual elevation view of the right side of a typical symmetric equipment arrangement.

odd/curious shape distortions that inevitably form in these difficult rolling operations.

Characterizing the Mill

Mill and Shape Actuation — This study will examine stainless steel products rolled on a reversing, solid-block ZR23-26 20-high Sendzimir/cluster mill (capable of 650 mm strip widths). This type of precision mill is well-suited for these types of hard, thin applications. Further, it's well-suited for this study because it is symmetric, highly instrumented, with precision, high-performance controls and extensive data acquisition.

This class of mill employs a monoblock housings, the roll cluster geometry and solid block mandrels to form a very stiff overall mill arrangement.[9] Their well-supported, small, chockless work rolls provide high reduction capacity and can be changed quickly (to adjust work roll crown and/or surface finish).[1] As shown in Fig. 3, the mill's associated equipment typically includes pairs of symmetric (right/left sides of the mill) x-ray gauges, laser speed/length systems, shape measurement rolls, strip edge sensing (for partial edge zone compensation) and closed-loop tension control. The mill and multi-speed gearbox winders are individually powered with 932-kW (1,250-HP) motors capable of rolling to speeds of 600 mpm.

As shown in Fig. 4, precision AGC is screwdown actuated through high-resolution gap position control

The bottom line is that this thin, hard, smooth material is non-trivial, so a certain amount of finesse is often involved in this special class of cold rolling. The real "trick" is having a clear understanding of the thin, narrow material, the wide mill rolling it, and how their complex interactions can be systematically and beneficially utilized to achieve the rolling objectives.[3,4]

Previous articles in this series[5–8] have introduced and explored a systematic methodology (for characterizing rolling mill behavior and coordinating the mill setup and scheduling) that assists in directing resolutions of shape-related issues. The intent of this case study series is not to develop the mill setups, pass schedules or shape target progressions needed to roll this complex, narrow material; rather, the focus is on utilizing these procedural strategies[6,8] to address

Figure 4

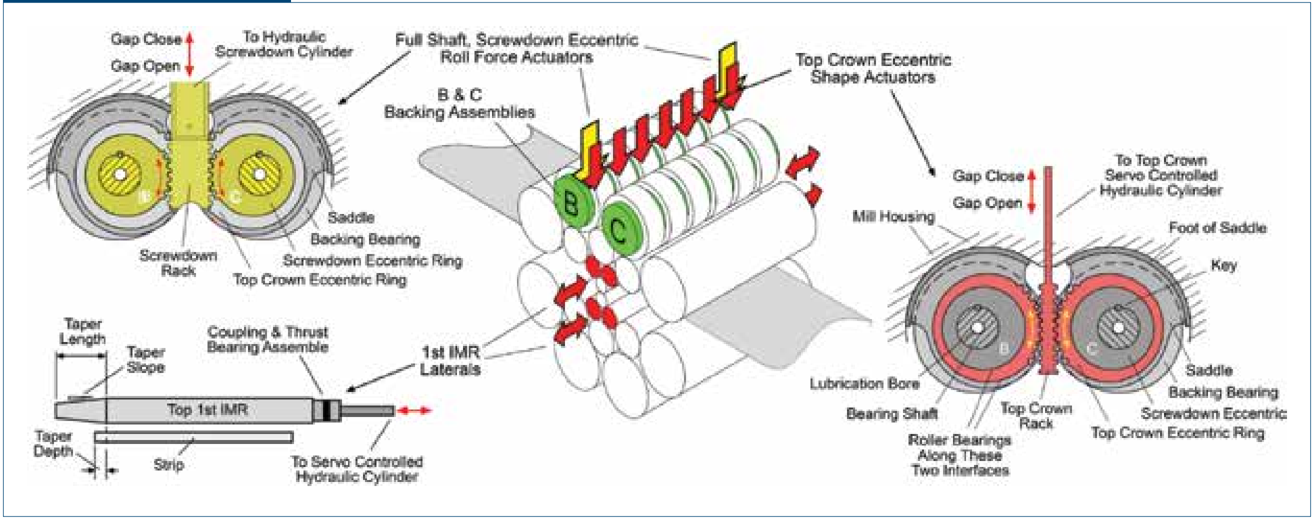
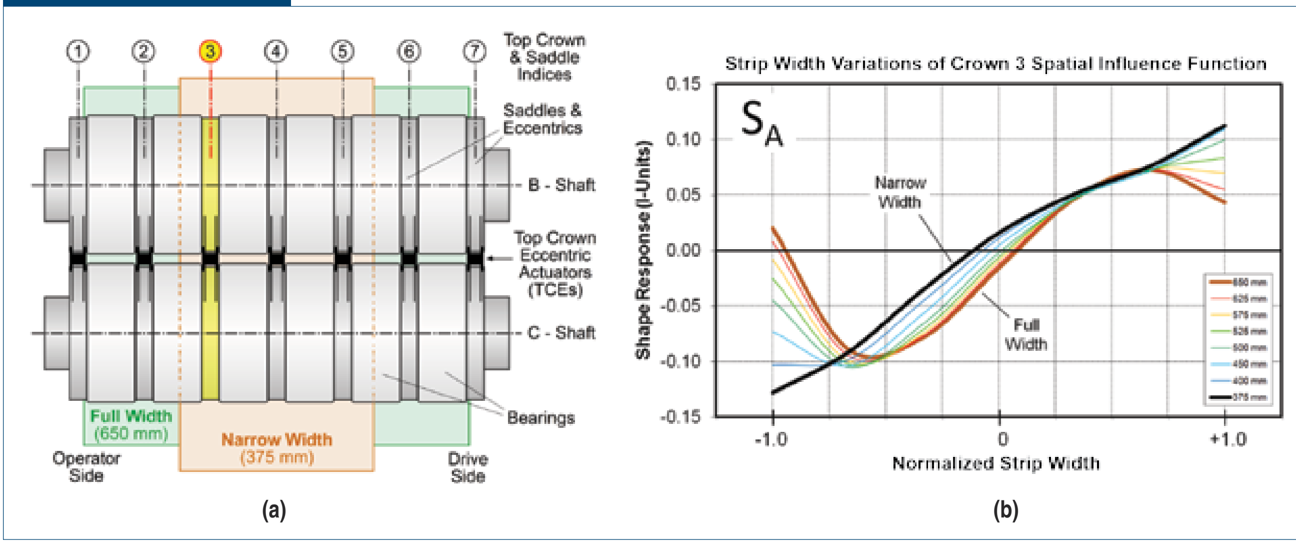


Illustration of the shape actuation systems.

Figure 5



Indications of: B and C shaft top crown eccentric (TCE) geometry/spacing over the range of strip widths (a); and Crown 3 spatial influence function/waveform pattern variation related to strip width (b).[5]

(~1/20 micron), coordinated with the speed/tension controls. Shape actuation is through precision hydraulic servo controls applied to seven top crown eccentrics (TCEs) (operating on the B and C shafts' six bearing flexible shaft backing assemblies (FSBAs)) and the tapered, lateral shifting, first intermediate rolls (IMRs).[1]

The mechanically ground "taper" profile can be specifically adjusted to accommodate the strip width (taper length); however, the fixed transverse geometry (spacing) of the TCEs will cause their capabilities to vary over the range of strip widths. Fig. 5a shows the relation of the B and C shaft top crown eccentric/bearing geometry to the range of strip widths. The full-width strip experiences the highest resolution of TCE actuation and the narrowest strip has only three TCE actuators operating over the interior of the strip.

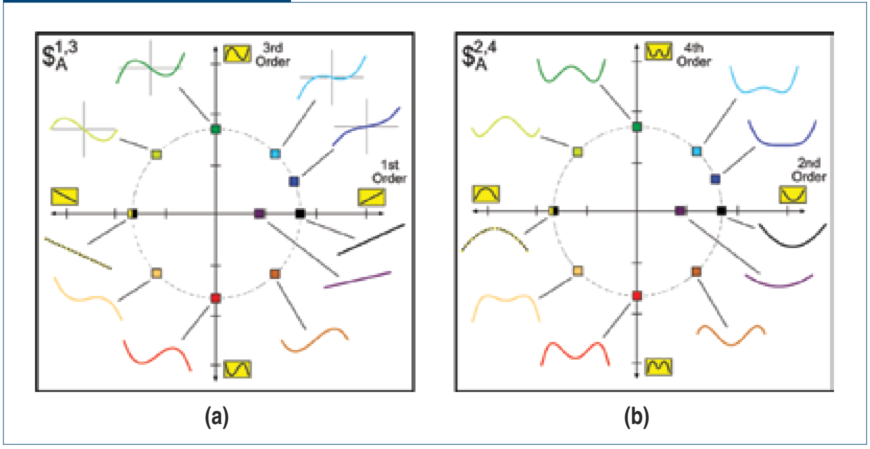
Each actuator induces a unique transverse stress adjustment pattern/reaction that can be characterized by a continuous spatial influence function/waveform. These spatial influences are not localized to the vicinity of the actuator's physical location, but span the strip's width, due to the manner in which the roll cluster mechanically reacts/deforms and distributes the actuator forces to form an equilibrium in the roll bite. Fig. 5b shows the variation in the transverse waveform structure of the Crown 3 influence (shape adjustment) over the range of strip widths. The root of this variation is the geometric location of the Crown 3, with respect to the strip, which transitions from deep in the interior (full width) to near the edge (narrow). On narrow strip, Crowns 1 and 2 are outboard of the strip edge and can only offer limited edge-bending capabilities. Other variations in the influence function patterns are related to strip thickness, yield stress, etc.[6]

The variability of the shape actuators' waveform functions creates difficulties in assessing how to accommodate shape distortions. The raw waveform structures provide no indications/guidance of how to proceed when confronted with complex shape problems. Recent developments[5,6,8] have formed a means of utilizing a waveform curvature space (based on a Gram orthogonal polynomial coordinate system[5]) to depict the shape actuation capabilities, characteristics and their interactions with the incoming strip; the mill's natural force-loaded deflection; and shape targets. As shown in Fig. 6, each multi-curvature waveform has a unique vector representation.

By evaluating the rolled shape's curvatures over the entire range of shape actuator settings (including the presence of physical and operational constraints), the resulting points (vectors) will map out a region in the curvature space. A bounding, piece-wise, continuous closed curve/surface can then be drawn along the extremities of the collection of plotted points, forming a closed region. This bounding surface functions as an overcontaining envelope that defines the extent of the mill's shape actuation capabilities (i.e., shape actuation capabilities envelope (SACE)[5]). Fig. 7 shows the SACEs for variations in strip width.

As the strip narrows, the extent of the SACEs diminishes, indicating that the overall shape actuation system loses dexterity and cannot provide high orders of corrective curvature. Narrow/localized shape defects possessing high-order spatial curvatures cannot be corrected by shape actuation. It's important to

Figure 6



Curvature space waveform mappings showing the spatial waveform structures/ patterns over a unit circle in: first- and third-order components (a); and second- and fourth-order components (b).

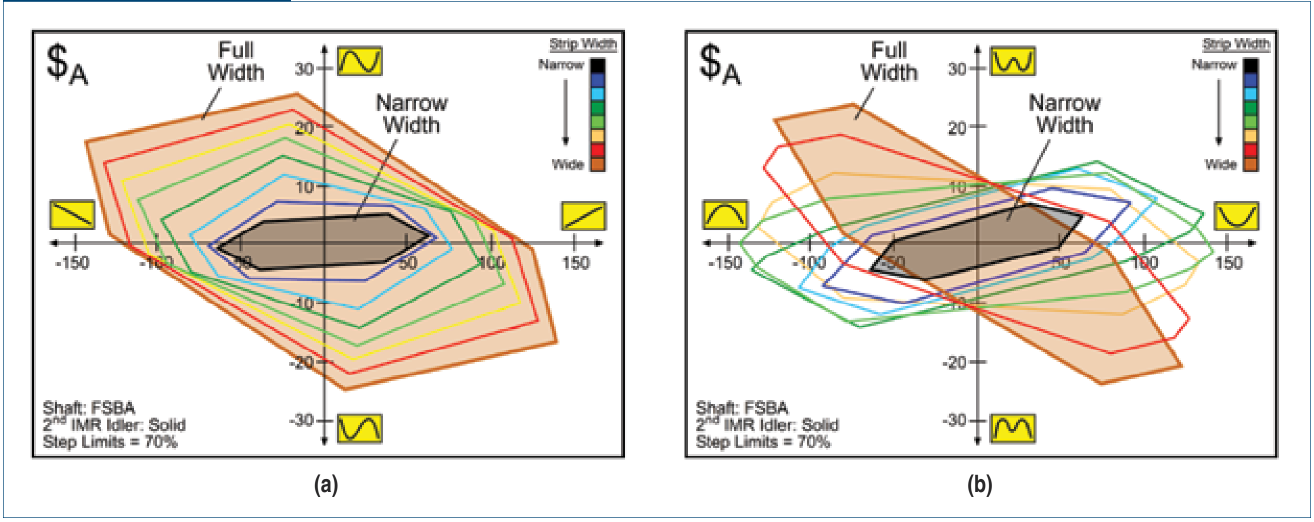
recall[6,7] that the SACEs also vary with material thickness, work-hardened yield stress, etc.

Shape Measurement and Control — The shapemeter sensor array provides wide (52-mm) zones located within the interior strip body, with narrow (26-mm) zones providing improved strip edge measurement resolution. Partially covered edge zone compensation is provided with strip edge location measurements.

The closed-loop shape control system must take the width, thickness and yield stress–related variations in the shape actuator's spatial waveform characteristics into account to properly coordinate shape-correction actions. The shape controls must enforce and accommodate the shape actuation constraints,[1,6] including low rolling speed and contact friction–induced limitations in first IMR transverse response, requiring the TCEs to assume control of the edge regions (critically important during low-speed pass initiation and completion[9]). The shape controls may also interact with the AGC to compensate for acceleration/speed-related reductions in roll bite friction, requiring a gap-opening action by the AGC, thereby relaxing the force-loaded deflection of the roll cluster, requiring a quick-responding change in shape actuation (i.e., move the first IMRs out to "fill in" the relaxing gaps local to the strip edges). A similarly reversed action occurs during deceleration.

Mill Setup — The mill setup (i.e., the selection of the cluster's individual roll mechanical crown/diameter profile and the settings of the side eccentric and bottom screwdown cylinder) directly defines the manner in which the cluster deflects in response to force loading. The design of the mill setup is a key compensation component in mill's shape actuation and control framework,[1,3,4,6,8] and the selections will vary with the material, its geometry, and the reduction plan, and may follow several avenues/philosophies of preference.[1–4] Fig. 8 provides an overview of the mill setup

Figure 7



Shape actuation capabilities envelopes (SACEs) for variation in the strip width: first- and third-order curvature space (a); and second- and fourth-order curvature space (b).

Figure 8

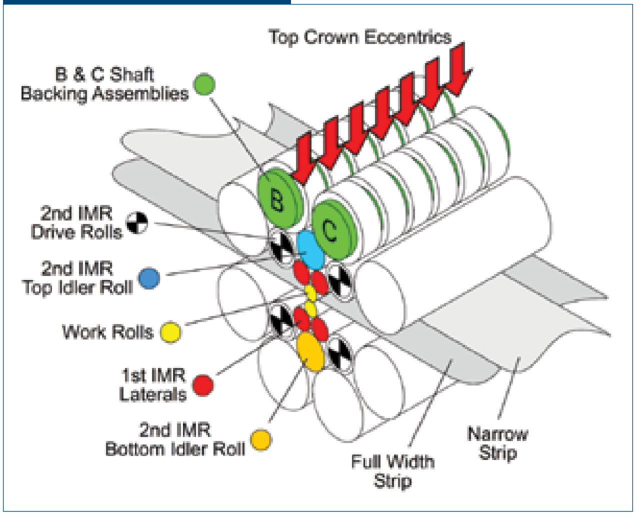


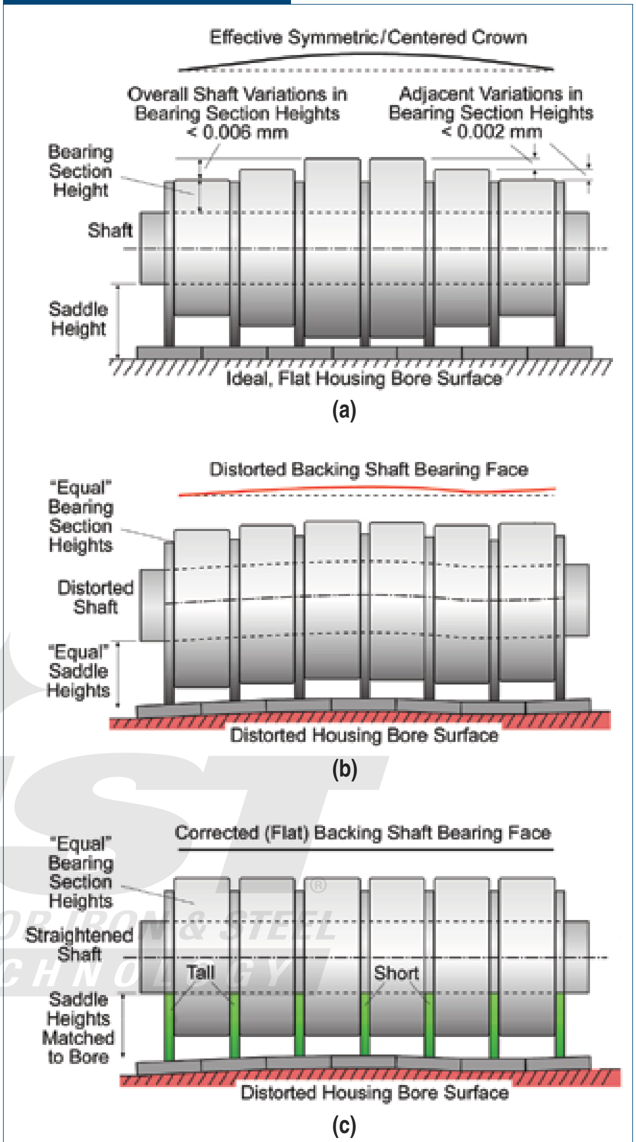
Illustration of the mill setup components.

Table 1

Typical Arrangements for Narrow Strip

Rolls	Roll diameter profile
Work rolls	Flat or crowned
First IMRs	One- or two-step tapers
Second IMRs	
Top idler	Flat
Bottom idler	Strip width crown
Drive rolls	Flat
Backing assemblies	Flat or slight crown

Figure 9



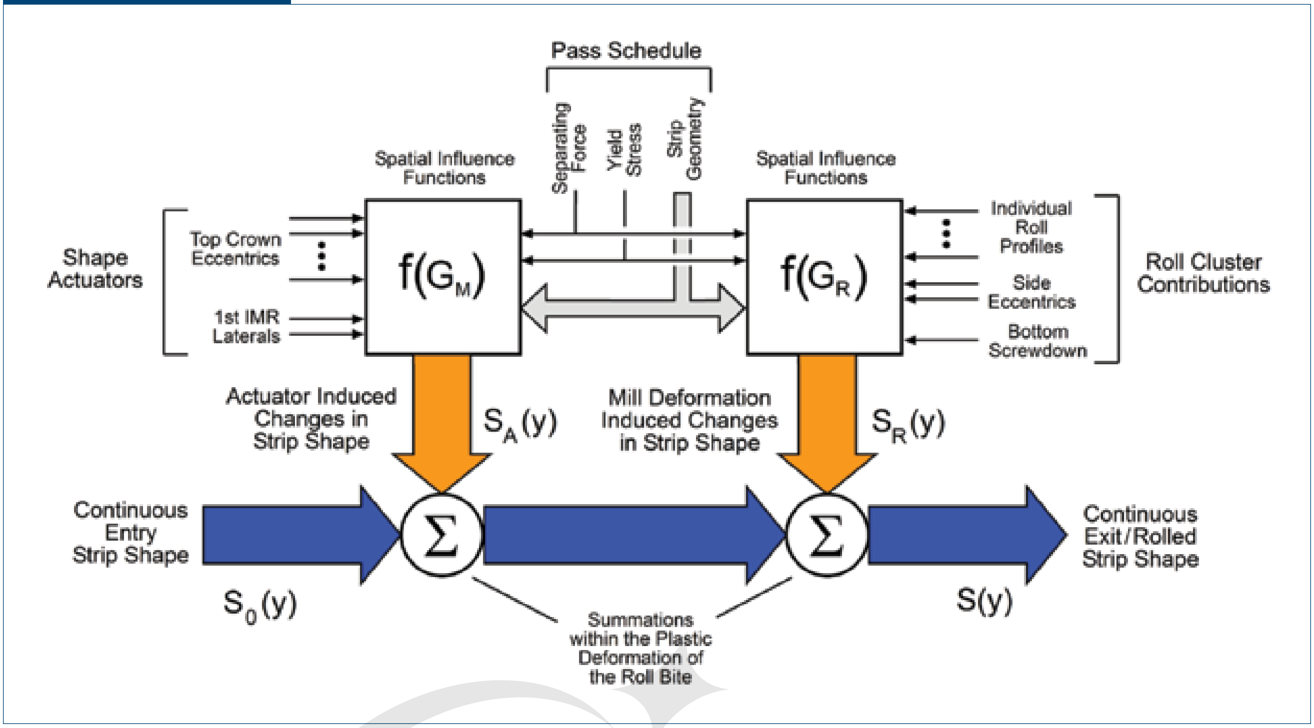
Backing bearing/saddle/shaft assembly practices: basic symmetric crowing on an ideal, flat housing bore foundation (a); resulting distortion from equal bearing and saddle heights applied to an uneven housing bore (b); and corrected assembly using selected saddle heights that match the bore distortion geometry, while preserving equal section heights (c).

components. Typical roll profiling philosophies/rationales are given in Table 1.

Typical backing bearing/saddle/shaft assembly procedures follow strict measurement/cataloging standards, along with systematic saddle location rotations and bearing selection to maintain specific bearing-to-bearing tolerances and achieve a baseline crowning. As shown in Fig. 9a, typical backing assembly crowning strategies work to achieve a symmetric crown effect, and do not attempt to compensate geometric anomalies occurring in individual housing bores (convexity, concavity and "kick"/taper). It is important to keep these anomalies in mind and how they may impact the transverse, unloaded roll gap (see Fig. 9b). As noted in Fig. 9c, in some cases, it may be necessary to specifically select and assemble the individual shaft's bearing/saddle combinations with compensating asymmetries that directly contour to the housing bore distortions, thereby providing a defined interior surface geometry (typically convex crowned) to the contact surfaces of the second IMRs.

A common approach is to apply "flat"/zero-crown, carefully matched second IMR drive rolls. The gravitationally held (more easily accessible and changeable) second IMR bottom idler can be specifically crowned to provide the primary "nominal" roll cluster crowning (i.e., force-loaded roll cluster deflection compensation) associated with strip width campaigns and reduction plans. The suspended second IMR top idler roll is more difficult to access and change, and can be crowned and/or tapered to provide a baseline

Figure 10



Block diagram showing the modeled components of the rolled strip shape, including the shape actuation's transverse spatial influence functions and the roll cluster deformation contributions.

correction of the combined effects of housing bore anomalies.

As noted previously, the first IMR taper lengths are based on the strip width and lateral adjustment range needed for edge region shape control. The taper slopes (or analytic functions) are selected to match and relieve the extent of force-loaded roll cluster deflection, local to the strip edge (related to the roll cluster setup, material geometry and work hardening, reduction plan, and resulting separating force, etc.).

Carefully selected, combinational work roll crowning is used to fine-tune the force-loaded roll gap geometry and compensate for subtle material profile and alloy anomalies that induce nominal, shape-impacting perturbations in the separating force, and resulting roll cluster deflection. In some cases, certain work roll crowning variations can be accommodated by changes to the pass schedule (i.e, changes to reduction, tension, speed, etc.) to make compensating changes to the operating point's separating force and cluster deformation.

Describing Mill/Material Interactions — In forming the rolled material, the mill and incoming material interact in complex ways.[1,3,4] As shown in the previous articles[5,6] and in Fig. 10, it is possible to describe this process as the transverse summation/superposition of the involved components:

Spatial waveform representation:

$$\mathbf{S}_T(y_M) \sim \mathbf{S}(y_M) = \mathbf{S}_0(y_M) + \mathbf{S}_R(y_M) + \mathbf{S}_A(y_M) \qquad \text{(Eq. 1a)}$$

where these components are the discrete, spatial representations (along the normalized, bipolar y_M)[5] of the contributing transverse shape/stress waveform patterns. These spatial waveform patterns have corresponding spectrums of ordered curvature, defined by Gram orthogonal polynomials.[5]

Spatial curvature representation:

$$\$_T \subseteq \$_S = \$_0 + \$_R + \$_A \qquad \text{(Eq. 1b)}$$

The combined definitions of these components is given by:

$\mathbf{S}(y_M) \Leftrightarrow \$_S \triangleq$ Rolled/existing strip shape pattern and associated spatial curvature spectrum.

$\mathbf{S}_T(y_M) \Leftrightarrow \$_T \triangleq$ Shape target pattern and associated spatial curvature spectrum.

$\mathbf{S}_0(y_M) \Leftrightarrow \$_0$ ≜ Incoming strip shape pattern and associated spatial curvature spectrum.

$\mathbf{S}_R(y_M) \Leftrightarrow \$_R$ ≜ Mill's mechanical deformation shape pattern and associated spatial curvature spectrum.

$\mathbf{S}_A(y_M) \Leftrightarrow \$_A$ ≜ Shape actuation–induced shape pattern and associated spatial curvature spectrum.

It's important to note that the mill deformation component, $\mathbf{S}_R$, is a composite formed from the interaction of the mill setup and material geometry/yield stress, at the operating point defined by the pass schedule. This component is static and cannot be modified during on-line/rolling operations. The shape actuation component, $\mathbf{S}_A$, is dynamic and can be modified/adjusted during on-line/rolling operations. The shape actuation's spatial influences of these mill/material-related components vary over the range of material characteristics and rolling conditions.

Understanding the Material and Mill Operations

Material Characteristics — This discussion will be based on a series of 304 stainless steel products, whose product mix and sequence are listed in Fig. 11. In this case, the rolling operations are not part of an integrated facility, and the full-width "base" material is purchased from several suppliers, having similar geometric tolerances and certain regional/commodities-based variances of the "in-spec" alloy chemistries.

The results of the upstream heavy-gauge breakdown rolling (see Fig. 1) are a series of full-width, center-crowned, annealed strips, rolled down to a thickness 2.0 mm, with sidetrimmed widths ranging from 1,025 to 1,240 mm wide. In general, the nominal, full-width, convex crown ratio is on the order of 3.5%, which corresponds to a measurable crown of approximately 70 microns. Although sidetrimmed, certain edge drop characteristics may persist, with an effective crown exceeding 100 microns.

After the heavy-gauge breakdown, the full-width strip is slit into two or three segments (malts) and applied to the finishing stages.

Of interest are the narrow-wedged strip products derived from the edge cuts (see Fig. 2). These wedged products are nominally 350–450 mm wide and can have a relative wedge approaching 2–2.5%. The incoming wedged coils may be geometrically conic, but dishing is unlikely at this interstage.

Mill Scheduling and Operations — The final stage delivered coils are a difficult-foil-class (50-micron-thick), high-yield-stress, spring product. The delivered material is strongly work-hardened (83% total reduction) and is typically rolled on a smaller, narrower ZR33-18 mill; however, production pressures may require that a reasonable amount of this product be rolled on the ZR23-26 (in question) using a nominal 9-pass schedule. In rolling this narrow material, the wider-faced ZR23-26 will operate at low separating forces (looser cluster) and possibly below face.

As previously discussed,[6,8] a pass schedule is a sequential, pass-by-pass series of mill reference settings and conditions that form a process by which the rolling and production objectives are achieved (typically, the desired last-pass thickness at an overall production rate). In general, pass schedule designs focus on the nominal behavior of the roll bite, reduction process and rolling conditions formed in a longitudinal plane positioned along the centerline of the rolling axis. The result is then uniformly distributed across the transverse roll gap,[10–15] without consideration of the transverse deflections/distortions that would actually result.

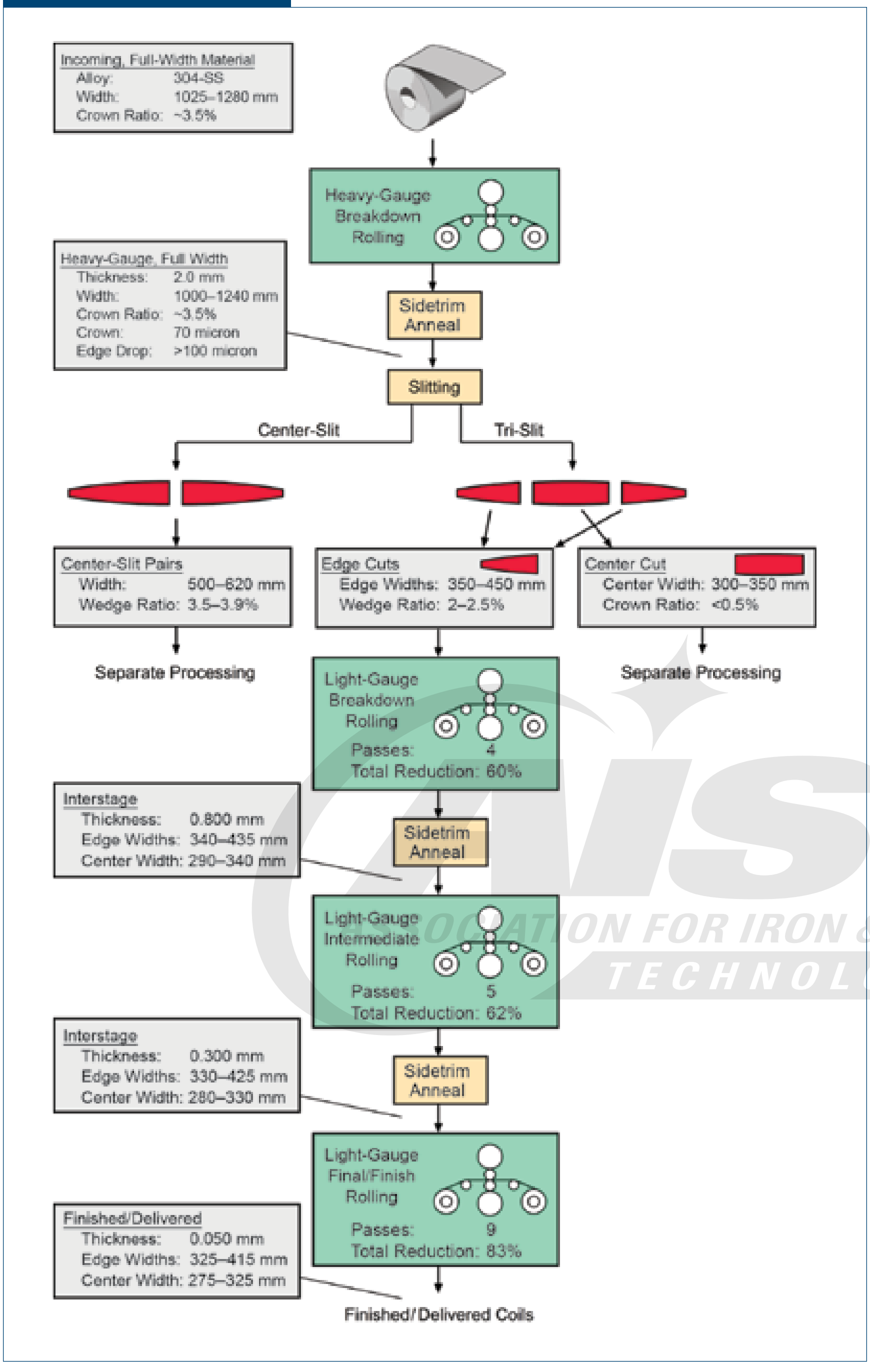
This study will not debate the philosophies or methods of pass schedule or shape target designs. The current operating plans and practices are accepted as a form of multi-variable initial condition; then on a pass-by-pass basis, the mill and material performance will be evaluated. From these results, adjustments will be made to the pass schedule, shape target progression and/or mill setup that follow the analytic suggestions in the directions of improvement.[6,8]

Description of the Problem

Rolling the thin, narrow, wedged material, the ZR23-26 requires a certain amount of operational finesse, and regularly experiences a narrow (50–75 mm wide), pocket-like, longitudinal buckling defect (pucker), appearing approximately 100 mm from the operator-side edge, when the wedge strip's thicker side is located/oriented to the operator side. The defect appears in both directions and manifests only when rolling the thin, last passes. In some cases, a degree of planar shearing exists and the longitudinal defect transitions to a diagonal buckle (but not herringbone). Fig. 12 provides indications of the nature of this curious defect.

Fig. 13 shows the general arrangement of the shape measurements, the defect location and the positioning of the first IMR taper depths. The ~415-mm strip is offset 10 mm from the mill centerline due to a conic coil-dishing effect to the thicker side (operator side). This causes a usable partial-zone coverage on the drive side and an excluded partial coverage on the operator side. This provides a shape measurement indication that is symmetric with the mill centerline (which induces a slight error in the registration of the shape actuation to the actual strip location). The

Figure 11



Block diagram showing the material characteristics and process flow with special emphasis on the narrow, wedged edge-cut regions.

important factor is that the shape measurements have sufficient edge resolution to witness and report the presence of the defect (shown as a narrow, very loose region).

The taper depths of the first IMRs typically operate approximately 25–40 mm from the strip edges. The 2-step, taper-knee transition distortions transmitted through the work roll do not occur in the defect's area (~100 mm from the operator-side edge), and therefore taper-knee effects[1] were not believed to be a source of the defect. The top first IMR's shape actuation responsibilities and proximity to the strip edge do not provide any shape correction capacity in the deeper embedded region of the defect.

Unfortunately, the TCE shape actuation spacing, registration and limited adjustment curvatures (see the narrow strip indications in Fig. 5) offer no ability for the TCEs to address this localized defect.

Essentially, the nature and location of the defect exceeded the mill's shape actuation capabilities, providing no means to address the defect with the mills' shape actuators ($\mathbf{S}_A$ in Eq. 1a and Fig. 10).

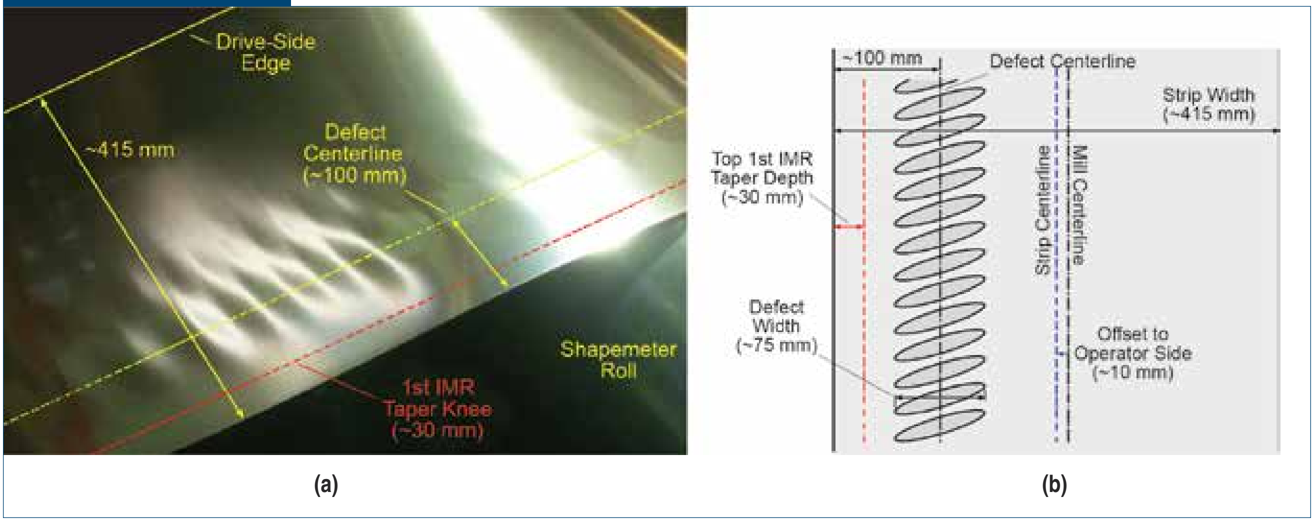
The focus turned to the mill setup ($\mathbf{S}_R$) and incoming strip ($\mathbf{S}_0$).

Initial Attempts of Defect Resolution

— The defect's size and localization initially pointed the focus of interest to the coolant spray bars/nozzles, but proved to be an immediate dead end. The next direction of focus concerned work roll crown wear and thermal growth patterns and the nature/severity of the first IMR tapers and single-step, taper-knee transition. Careful perturbation testing and evaluation determined that these components were not direct sources of the difficulty, but did play contributing roles in the fine details of the defect's shape pattern. During the testing and rolling trials, other (unrelated) shape performance improvements were noted, leading to the use of 2-step tapers as a standard operating practice. The incorporation of the 2-step tapers provided no significant improvement in the defect resolution. Subsequent studies considered the backing assemblies, roll grinding procedures, and strip wiping, but yielded no evidence of a "smoking gun."

The problem appeared to be a complex interaction between the strip's specific transverse profile

Figure 12



Photograph (a) and diagram (b) showing the nature, location and geometry of the defect.

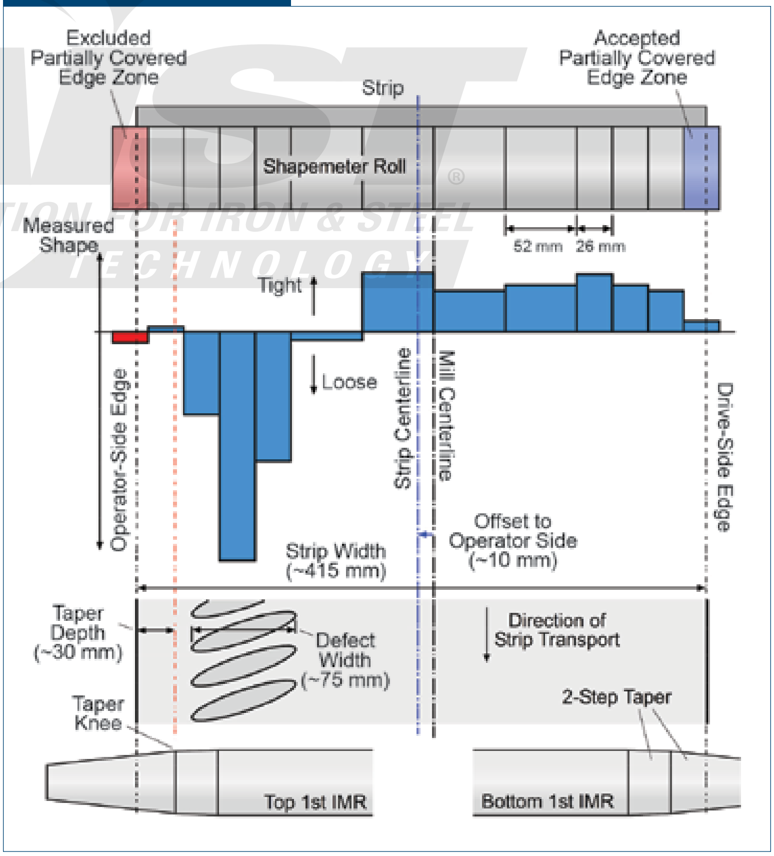
and the fundamental deformation characteristics of the mill ($\mathbf{S}_R$). The plan was to employ multi-variable analysis[5–8] and form a series of suggested "directions" of improvement.[6,8] The real trick in applying multi-variable methods is measuring the mill behavior and gaining insight into how the mill/material interact.

Conclusion

An interesting and vexing problem in the rolling of narrow, thin strip having an asymmetric transverse thickness profile on a wider mill has been presented and discussed. A difficult shape distortion is regularly experienced and is not amenable to the conventional remedies of shape actuation and changes to the mill's roll cluster setup. What is known is that the root cause of the shape distortion lies somewhere in the interaction of the mill and material during the rolling of the thinnest final passes, where the strip is strongly work-hardened and most likely to expose shape defects.

This article is the first in a two-part case study and has set the stage for an investigation into the underlying cause and a determination of resolution. The second article will employ a combination of direct, empirical testing (both on-line and off-line) and analytic scrutiny to gain insight into the mechanisms of the shape distortion's formation. Using a recently developed multi-variable analytic method, the pathway to resolving this problem will be exposed and understood. This pathway/direction of improvement will suggest various combinations of

Figure 13



Shape measurement registration with the offset strip and indications of the 1st IMR taper knee locations.

interacting compensations, thereby offering several optional arrangements. The merits of each approach will be discussed and weighed (from a practical standpoint), and the available flexibility in the upstream activities in the multi-stage rolling process will be considered.

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Did You Know?

SSAB, LKAB and Vattenfall Launch Initiative for a Carbon-Dioxide-Free Steel Industry

SSAB, LKAB and Vattenfall have announced that they are launching an initiative to solve the carbon dioxide problem in the Swedish steel industry. Together, the companies involved will initiate work to develop a steel production process that emits water rather than carbon dioxide.

The world is facing major challenges in the quest for a more sustainable society. SSAB's existing production system is already one of the world's most efficient in terms of carbon dioxide emissions. Nevertheless, existing steelmaking technology using coke plants and blast furnaces means SSAB is Sweden's largest single source of carbon dioxide emissions.

SSAB, LKAB and Vattenfall together are prepared to assume major responsibility to find a long-term solution to the carbon dioxide problem in the steel industry. Consequently, the companies concerned have announced that they are launching a joint industrial development project to create steel production that emits water instead of carbon dioxide.

With its specialized, innovative steel industry, access to fossil-free electricity and the highest-quality iron ore in Europe, Sweden is uniquely placed for such a project.

"The environment and sustainability have been a part of SSAB's long-term strategy for many years. But we want to do even more. Under this initiative, we will take responsibility to solve long-term the problem of carbon dioxide in the steel industry," stated Martin Lindqvist, president and chief executive officer (CEO) at SSAB.

"LKAB makes iron ore products using processes that require less energy and result in fewer emissions than the majority of our competitors. Our focus lies on also optimizing our customers' processes. This drive for carbon-dioxide-free ironmaking will be a significant contribution to sustainability," says Jan Moström, president and group CEO at LKAB.

"It is very pleasing to take part in an initiative to secure the future of one of Sweden's important branches of industry by using carbon-dioxide-free electricity to replace fossil fuel in steel production. This is the start of a highly interesting, climate-friendly development project that benefits our partners, Vattenfall and not least the climate," says Magnus Hall, president and CEO at Vattenfall.

The project will also mean a major contribution to a fossil-free Sweden. Implementation of the project will also require national contributions from the state, research institutions and universities over the next 20–25 years.

"Sweden has the chance to take the lead in this matter. No other country in Europe has the same opportunity thanks to the competence of our three companies and country's unique natural resources. Nevertheless, success requires strong political involvement and commitment. Our three companies have a clear future vision: together we can create a more sustainable future, where one of the goals is steel without coal," Martin Lindqvist concludes.