Recent Technological Advancements at the Faircrest Steel Plant

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INTRODUCTION

Recent capital investments to the Faircrest Steel Plant (FSP) allow for additional capacity, manufacturing flexibility, superior cleanness for strand cast products, increased soundness in large bar sizes, verification of large bar center soundness, and an overall broader capability to support higher value special bar quality (SBQ) and seamless mechanical tube markets. Commissioning of multiple pieces of equipment (shown in Figure 1) – jumbo vertical bloom caster (2014), second ladle refining station (2013), inline forge press (2013) and ultrasonic inspection line (2012) – provide the basis for exploring the key material properties, processes and methodologies necessary for advancing new and challenging long products to our customers. Forethought given to these investments allowed TimkenSteel to address key quality advances during the planning and design phases. The integration of metallurgical modeling as a tool for understanding process design and optimization also contributes to the flexibility gained through these capital investments. Process design for center soundness and steel cleanness are at the forefront of the discussion related to these strategic technology investments and are the two main technical subjects discussed in this paper.

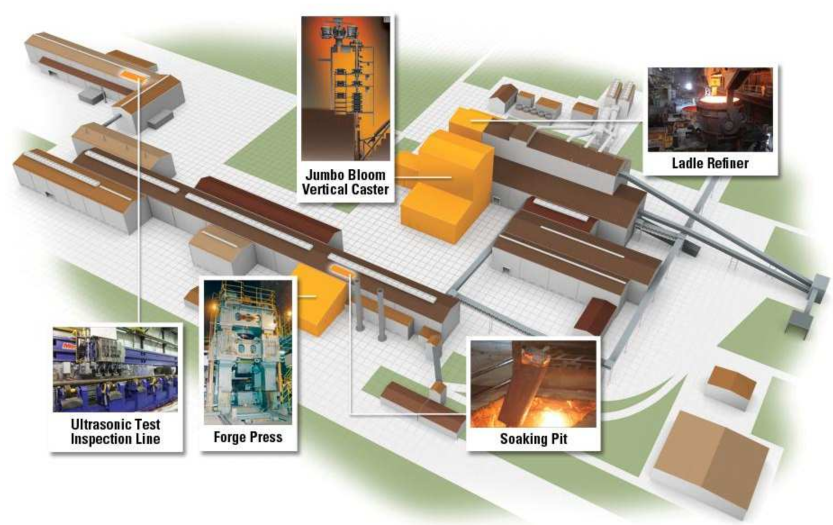

Figure 1. Map of the Faircrest Steel Plant showing the locations of recent strategic capital improvements - jumbo vertical bloom caster (2014), second ladle refining station (2013), inline forge press (2013), ultrasonic inspection line (2012) and additional soaking pit reheat capacity (2011).

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DESIGN FOR CENTER SOUNDNESS

Strategic Investment - Inline Forge Press and Ultrasonic Inspection

In 2013 a 3000 metric ton inline open-die forge press started up on time at FSP without disruption to production. The investment is in direct response to customer requests for TimkenSteel high-quality melt in larger rolled sizes (greater than 9 inches) with sound centers. This addition created two process paths for long products at FSP – rolled-only and forged-rolled. Rolled-only material continued to bypass the forge press as a part of the previously established process, while ingots and blooms destined to be forged-rolled bar product experienced one or more forging passes on the new inline open-die press.

Center soundness specification

With improvements in center soundness provided by the inline forge press came the need to validate and quantify the center quality. Visual and material density measurements are impractical to use in a production environment due to their small sample size and destructive nature. Calculated reduction ratio, Equation 1, has historically been used in lieu of a quantitative measurement of center soundness. Reduction ratio, RR, is the ratio between the initial cross-sectional area, A_i, and the final cross-sectional area, A_f. Reduction ratio limits have historically been specified for single process conversion paths (either rolling or forging).

$$RR = {}^{A_i}\!/_{A_f} \qquad (1)$$

Since the comparison between final bar quality was using an equivalent process history comparison (rolled vs. rolled or forged vs. forged), the relative relationships were valid enough to establish standard center soundness specifications for a given steelmaker's process (despite differences created by process variations). However, because reduction ratio does not actually quantify center density (it is strictly geometric), standardization across multiple steel sources is challenging – leading, in some cases, to overly conservative reduction ratio specifications. The forged-rolled process incorporates both aforementioned deformation methods, so a single designation for reduction ratio is no longer as effective for comparing versus historical rolled-only or forged-only reduction ratio specifications. The installation of a large bar ultrasonic testing (UT) inspection line at FSP allows for the non-destructive evaluation of soundness requirements in forged-rolled large bar. UT results close the feedback loop between forged-rolled process recipe development, computational modeling of proposed recipes and the actual center soundness level.

UT inspection of bars is a non-destructive evaluation method for characterizing the soundness and/or homogeneity of long product. UT evaluation utilizes the reflection of ultrasonic sound waves to gauge the internal quality of products. Unexpected reflections may be indicative of heterogeneities in the bulk of the bar[1]. Quality specifications for UT evaluation are related to the frequency and estimated size of the documented indications. The raw UT result is the reflected indication screen height as calibrated to an estimated heterogeneity size through the use of a range of specially machined calibration bars

Summarized UT results, such as the bar diameter versus indication frequency shown in Figure 2 help define quality capabilities and provide calibration and validation support for advanced process simulation efforts. By establishing this additional link (in conjunction with targeted in-plant trials) between simulated and measured product quality, a majority of product can be produced without required UT inspection beyond an initial start-up approval phase.

Forged-rolled large bar soundness optimization

Increased levels of center soundness are achieved through the healing of remnant as-cast microporosity. The scope of this paper discusses shrinkage microporosity, and any further reference to 'microporosity' should be assumed to be of the shrinkage variety. Shrinkage pores are created when there is inadequate connection to the remaining liquid steel during casting, causing them to remain isolated in the final as-cast structure[2-4]. This focus on soundness stems from research that shows it is the remnant as-cast microporosity which can cause lower mechanical and fatigue properties in the as-cast state. However, once this microporosity is healed (through hot deformation) properties increase and plateau at wrought behavior levels[5-8]. Understanding the entire process path and the product soundness at each step is critical to implementing an optimized process for center soundness. Utilization of in-plant trials, non-destructive techniques and computational simulation software facilitated the comparison of soundness quality between rolled-only and forged-rolled large bar. Of

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primary interest is tracking key simulation results throughout the entire casting-to-bar manufacturing process path to provide a clear picture of center soundness evolution.

This comprehensive understanding starts at casting – by identifying the starting condition of an ingot or bloom. Initial mitigation of microporosity occurs during steelmaking by controlling the casting design and process parameters. By designing and selecting the process parameters (such as ingot mold shape, material superheat, mechanical soft reduction, and ingot filling rate or continuous casting speed) for a given material composition the occurrence of microporosity can be minimized in the as-cast state[9]. A combination of physical sectioning and computational tools provide the size and intensity of internal porosity remaining after casting. Microporosity which is not prevented through casting process optimization can be healed through further hot working. However, forging and rolling each have separate contributions to the improvement of center soundness as White, et. al stated - *"Hot work eliminates porosity, but the amount required to produce full density in bars is a function of the method by which the hot work is applied[5]."* Computational simulation tools are used to characterize the deformation (forging, rolling) processes as they relate to microporosity along the centerline of cast product. It is found that the maximum deformation during the rolling process occurs at localized regions of the bloom/billet/bar surface where the rolls are in contact with the work piece (as shown in a simulated bar cross-section in Figure 3a) providing good final shape control. Open-die forging, on the other hand, allows deformation to penetrate throughout the whole ingot or bloom cross-section during a given forging hit (as shown in a simulated bloom cross-section in Figure 3b) providing the necessary centerline deformation to heal remnant as-cast microporosity.

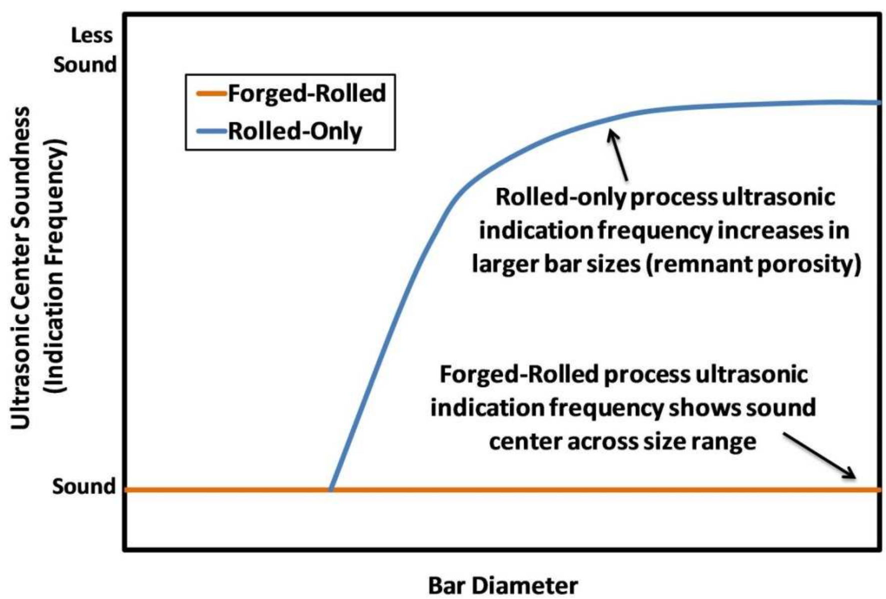

Figure 2. Figure showing the capability of the forged-rolled and rolled-only process. Rolling deformation can leave remnant porosity in larger bar sizes due to the surface-concentrated nature of the deformation. The forged-rolled process is able to fully consolidate the center material and produce large bars which conform to stringent pass/fail soundness specifications.

A simulation procedure has been developed for tracking the soundness improvement from casting through final bar product by identifying a combination of stress, strain and density related variables which reflect the internal soundness throughout the deformation process. This soundness tracking parameter is used offline to assess process path changes and direct optimization efforts. A trial was performed to demonstrate the difference between a non-optimized and optimized forged-rolled process sequence. Figure 4 shows a comparison of simulated soundness tracking parameter results for two trial forged-rolled process sequences as well as the associated measured UT indication profiles. There is clear alignment between the UT indications and regions which show lower values of the soundness tracking parameter. The optimized forged-rolled sequence shows that when a critical amount of the soundness tracking parameter is achieved along the length of the work piece the final bar passes UT inspection without indications. It is important to note that the overall starting condition (material, cast bloom size) and final rolled bar size (and thus geometric reduction ratio) are identical for the two examples shown in Figure 4, yet only the optimized forged-rolled sequence produces a sound product which meets the required UT specification.

Shifting paradigms from the geometric reduction ratio calculation and focusing instead on the deformation necessary to create a sound large bar facilitates a methodology that allows TimkenSteel to produce a sound, large bar product

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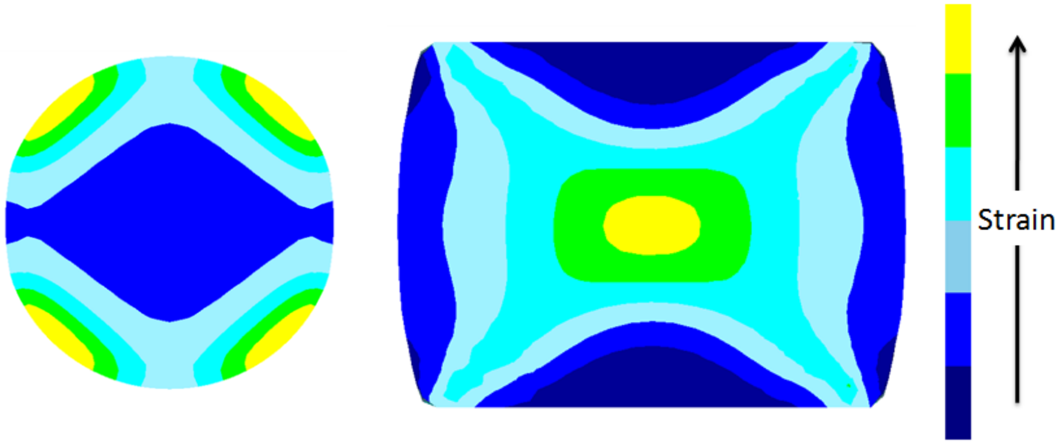

(a) (b)

Figure 3. Simulated characteristic strain patterns produced during (a) rolling a quadrilateral to a round and (b) open-die forging. Rolling deformation is localized on the surface, especially near the breakdown of the prior corners, while open-die forging is capable of creating peak strain values at the core.

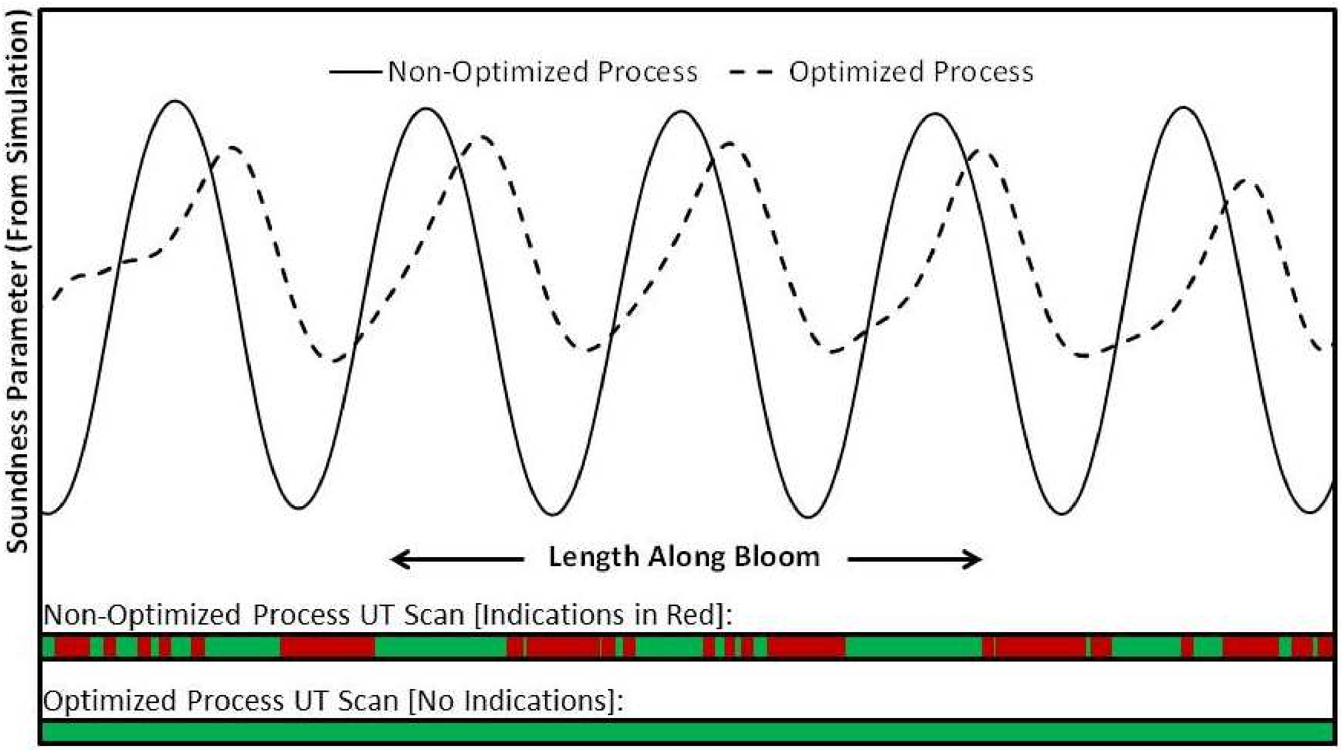

Figure 4. A plot showing the simulated soundness tracking parameter results for two forged-rolled processes – non-optimized and optimized. Both processes share the same starting and final bloom conditions. Below the plot are results from two centerline UT scans showing the indications produced by the two process sequences as measured against a Class B ultrasonic limit (Class B is equivalent to a 1/8th in flat bottom hole). Evident in the non-optimized UT scan are the remnant porosity indications (red) that align with the lowest values of simulated soundness tracking parameter; however indications are not present in the optimized process due to a sufficient level of the soundness tracking parameter being reached along the entire length of the bar.

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at reduction ratios lower than historically acceptable in the rolled-only process path. The forged-rolled process combines the beneficial centerline deformation produced in open-die forging, as shown in Figure 3b, with the mature dimensional control produced through rolling deformation, as shown in Figure 3a.

DESIGN FOR SURFACE QUALITY AND STEEL CLEANNESS

Strategic Investment - Jumbo Vertical Bloom Continuous Caster and Second Ladle Refiner

In 2014 TimkenSteel Corporation cast the first heat through its new jumbo vertical bloom caster, the largest of its type in the world. This vertical continuous casting machine, illustrated in Figure 5, was cooperatively designed by SMS Concast and TimkenSteel. To facilitate the smooth start-up of the caster a second ladle refiner was installed ahead of the caster in 2013. Refining is a key process step and the addition of a second refiner allows for manufacturing flexibility, less downtime and expanded capability to make grades which require extended refining times. The addition of a second refiner also ensures swift delivery of steel to the caster as needed.

The decision to incorporate a vertical design for the new FSP caster was based on several factors, but of critical importance was the impact on steel quality. There are several significant quality benefits inherent in the basic design of a fully vertical continuous casting machine. The primary benefit is the potential to make steel with superior cleanness. Second, the vertical design provides a more symmetric axial solidification and segregation pattern as compared to a curved-mold caster. And third, there are no unbending strains with a vertical caster which allows TimkenSteel to cast a greater range of steel grades.

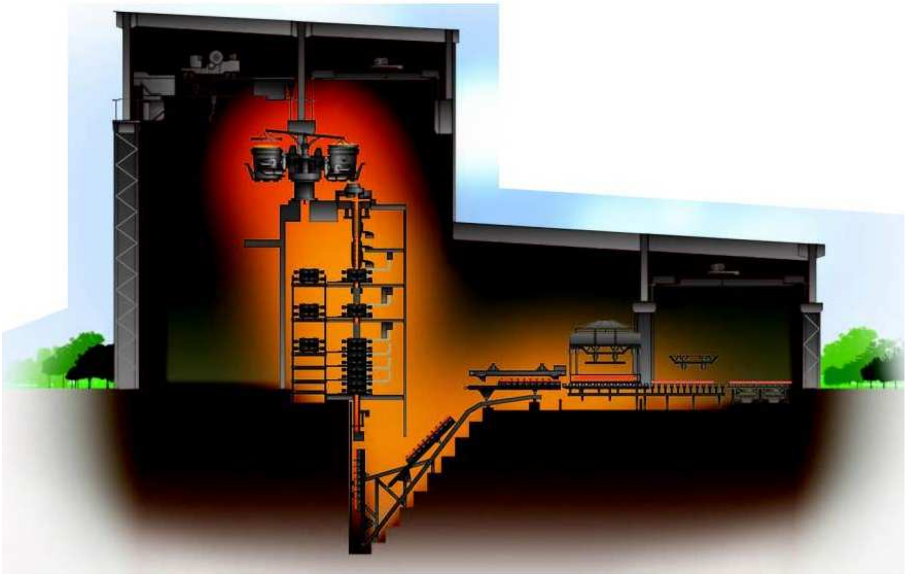

Figure 5. Illustrated side view of the new Faircrest Steel Plant jumbo vertical bloom continuous caster.

Cleanness

Perhaps the most recognized benefit of vertical continuous casting is the positive impact on steel cleanness (i.e., oxide inclusion population and distribution). Most continuous casting machines are curved mold or bow type. In those configurations the solidification front on the inside radius of the strand traps many oxide inclusions as they tend to float up, leading to, what is referred to as, an inside radius concentration of inclusions. The schematic diagram in Figure 6 illustrates the principle behind this phenomenon.

In an attempt to avoid or minimize this inside radius condition, vertical with bending casting machine designs were introduced. These designs can provide a range of steel cleanness improvement primarily depending on the length of vertical section employed and the corresponding operating cast speed. The removal potential of the oxide inclusions depends, in part, on the residence time in the vertical section. This, in turn, is dependent on the length of the vertical section and the casting speed. An illustration of this improvement in steel cleanliness is provided in Figure 7[10]. However, the improvement is generally not as significant as achieved with a fully vertical caster. Additionally, the vertical with bending design still introduces bending, as well as unbending, strains.

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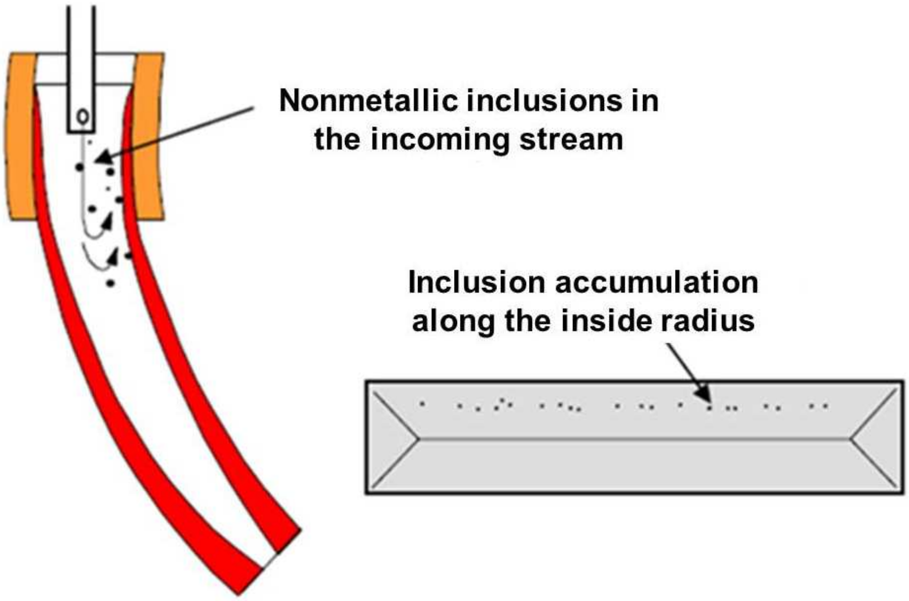

Figure 6. Basis for the formation of an inside radius concentration of oxide inclusions in curved mold casting machines.

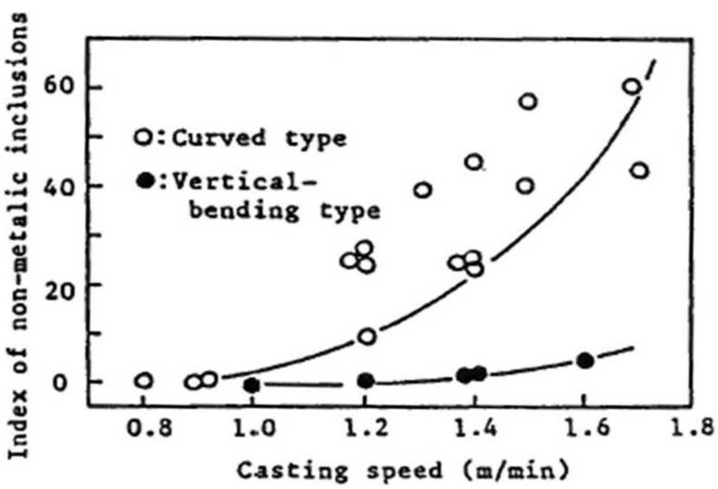

Figure 7. Plot showing the effect of caster design and casting speed on concentration of oxide inclusions.

In addition to the beneficial effect inherent with vertical continuous casting on steel cleanness, a special tundish design is utilized on the new FSP caster to further optimize the removal of potentially detrimental oxide inclusions. This new tundish design, in coordination with appropriate operational practices, focuses on providing cleanness improvements during periods of transition casting. Tundish design work incorporated traditional water modeling techniques as well as computational fluid dynamics (CFD) modeling. Utilizing both these methods allows for swift iterative design improvements toward the tundish design optimization goals – maximizing mean residence time in the tundish, controlling velocity and turbulence, maximizing inclusion floatation and eliminating dead zones with no flow.

Internal quality

Another quality benefit derived from strand solidification in a fully vertical orientation is a more symmetric solidification structure, i.e., the metallurgical and geometric centers of the bloom are coincident. This is not the case with curved caster designs. Schematics of respective as-cast structures, provided in Figure 8, highlight the difference. The alignment of the equiaxed zone and the axis of center segregation with the as-cast section's geometric center should provide more consistent distortion behavior. Accordingly, this should allow better prediction of distortion and a significant positive impact on distortion control of heat treated components.

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The new caster also employs dynamic mechanical soft reduction (MSR), the application of small amounts of deformation to continuously cast steel prior to full solidification[11-13]. MSR is found to improve center segregation and lower porosity in the cast steel bloom center when compared to conventional casting as shown schematically in Figure 9[11]. The active mechanism in the application of soft reduction is a mild compression force applied primarily to counteract the suction action of solute enriched liquid into interdendritic and central core regions due to solidification shrinkage. The dynamic aspect of the soft reduction system utilized on the FSP caster optimizes the beneficial effects by locating the application of compression force at the appropriate positions along the strand.

Surface quality

With regard to surface quality, a vertical caster does not require bending or unbending of the strand, as would occur in typical bow or vertical with bending machines. Accordingly, there are no stresses resulting from bending/unbending strains, thus eliminating a major source of transverse cracks. The absence of bending/unbending strains also facilitates the continuous casting of many high alloy crack sensitive grades whose manufacture are generally confined to a statically ingot cast practice. In addition to the benefits of no bending stresses, the vertical strand shell faces facilitate the uniform application of secondary cooling (spray water or air-mist), reducing the opportunity for severe thermal gradients within the solidifying shell and the resultant potential for crack formation.

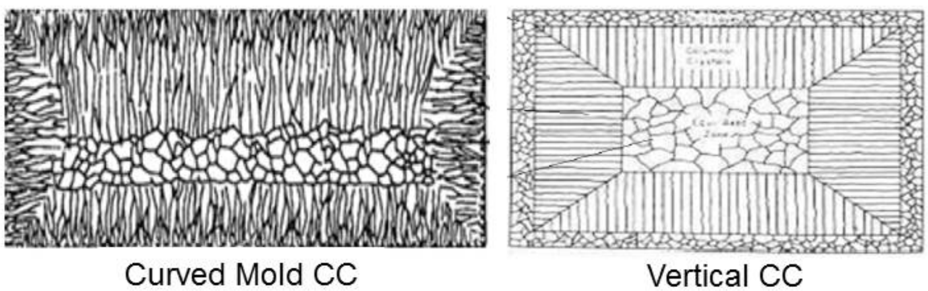

Figure 8. Drawings showing the difference in as-cast structures for curved mold (left) and vertical continuous casters (right).

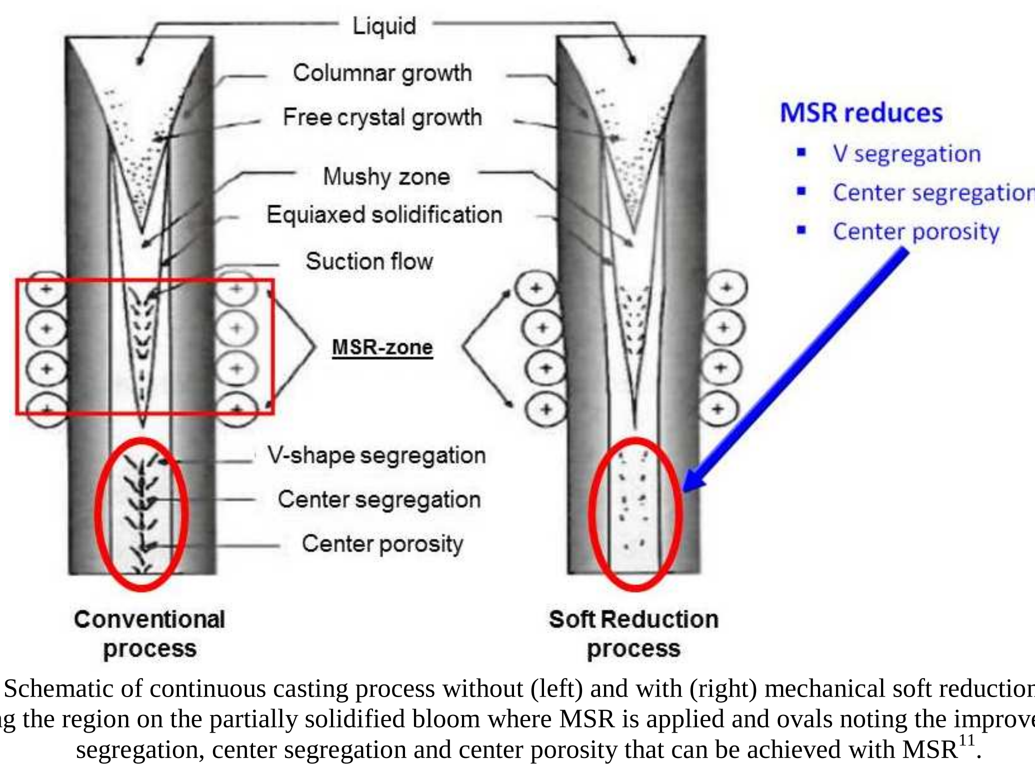

Figure 9. Schematic of continuous casting process without (left) and with (right) mechanical soft reduction. Note box indicating the region on the partially solidified bloom where MSR is applied and ovals noting the improvement in V segregation, center segregation and center porosity that can be achieved with MSR[11].

STRATEGIC TECHNOLOGICAL INVESTMENT

A multi-year series of strategic capital equipment investments has been completed at the TimkenSteel Faircrest Steel Plant. Significant effort and forethought contributed to these investments in order to ensure the desired collective impact on advancing technological steel producing capabilities. Key advancements were made related to large bar center soundness and steel cleanness.

With the introduction of the forged-rolled multi-process conversion path, which combines the beneficial centerline deformation produced in open-die forging with the mature dimensional control produced through rolling deformation, the center soundness paradigm shifts from the questionable geometric reduction ratio calculation to focus instead on the deformation necessary to create a sound bar as evaluated via UT inspection. This optimized methodology allows TimkenSteel to produce a sound, large bar product at geometric reduction ratios lower than historically possible in the rolled-only process path.

The start-up of the vertical jumbo bloom continuous caster continues the TimkenSteel tradition of producing some of the cleanest steel in the world. Through optimized machine and operational practice design, the new TimkenSteel vertical jumbo bloom caster provides a number of distinct quality advantages over most other continuous casting machines. Table I illustrates the relative effect of caster design on surface and internal quality, as well as steel cleanness.

Table I: Summary of Relative Impact of Several Quality Factors for Different Caster Designs

	Curved Mold CC	Vertical w/Bending CC	Fully Vertical CC
Steel Cleanness	**0**	+	++
Surface Quality	**0**	-	+
Internal Quality	-	**0**	+

Where “0” = No Impact, “-” = Negative Impact, “+” = Positive Impact, “++” = Significant Positive Impact

When taking all of these investments together it provides a highly flexible and efficient process path to deliver steel products to overcome our customer’s toughest challenges.

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