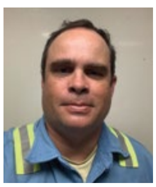
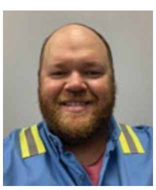
New Approach to Coil Sagging Control at ArcelorMittal Hot Strip Mills




The shape of hot-rolled coils must satisfy certain dimensional tolerances required for downstream processes and handling. Some steel grades are more susceptible to the so-called "coil sagging" — coil shape distortion when a coil is not perfectly round. An important factor responsible for coil sag is phase transformation of austenite during cooling after hot rolling, when a significant portion of austenite remains in the material during strip coiling. Aiming at keeping the coil shape at acceptable levels with less impact on hot strip mill productivity, ArcelorMittal utilizes several techniques of process optimization, including a new technology developed and patented by its Research Center in East Chicago. This article summarizes ArcelorMittal knowledge and industrial experience in this field.

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Introduction

Coiling and uncoiling are the necessary and important stages in manufacturing flat steel products. The rigidity of coils and especially the roundness of the inner diameters are crucial factors that ensure smooth transition from one operational stage to the next. Coil rigidity eliminates additional reprocessing that leads to substantial productivity losses in downstream processes and entails extra costs.

The loss of coil rigidity and deviation from round coil shape (Fig. 1) is a defect termed "coil collapse." Coil collapse can bring deleterious consequences during coil production, transportation and application.* Coil collapse is typically evaluated by either of two conventional criteria: (1) as the difference between the maximum D_{max} and minimum D_{min} inner diameters of a coil, $D_{max} - D_{min}$ (Fig. 2), or (2) as the relative deviation of the minimum inner diameter D_{min} from the nominal inner diameter D_{nom}, $(D_{nom} - D_{min})/D_{nom}$. Depending on the particular mill and manufacturing stage, the two coil collapse criteria are selected either as an absolute difference (in mm) or as a relative difference (in %). Both criteria provide metrics for coil conformity for mounting on mandrels in a downstream process. The above criteria render qualitative information on the potential uneven mass distribution of oval-shaped coil, which can cause unwinding instability, damage the equipment mechanical parts due to severe oscillations, can require special attention during payoff reel operations, "wobbling" of coil while uncoiling that result in strip steering issues, etc. Typically, an ovality of up to 50 mm or 7% is considered acceptable, although these values can vary for different processing lines. Higher values imply costly rework in reprocessing lines.[1]

The present work is focused on collapsing of hot-rolled steel coils, addressing a representative share of product mix grades that are highly susceptible to collapse. This article presents the result of joint effort by ArcelorMittal R&D and ArcelorMittal hot strip mills around the globe.

Root Causes of Hot Band Coil Collapse

Coil collapse is an indication of the inability of a coil to support its own weight,[2] which causes displacement of coil wraps with respect to each

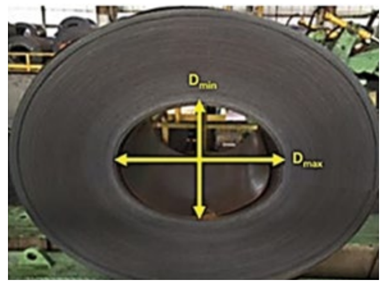
*Other terms: coil sag, coil slump, egg-shape, ovalization, etc., are often used.

Figure 1

Collapsed hot-rolled coils.

Figure 2

Measurements of coil diameters to quantify coil collapse.



other. It is generally accepted that 1 μm of slipping between wraps is equivalent to 1 mm of ovalization. Displacement (slipping) of coil wraps is determined by correlation between three major parameters: radial (normal) stress σ_n, tangential stress τ, and friction coefficient μ. Slipping of two adjacent wraps occurs if $\tau \geq \mu\sigma_n$.

The correlation between the above three major parameters depends on the variety of factors that can act individually or as compounding combinations. The multiplicity of these factors and their interplay make coil collapse a stochastic problem that still challenges scientific and industrial communities; there are still pending technological gaps that prevent getting complete, feasible and sustainable solutions.

Factors influencing the interplay between σ_n, τ, and μ and the propensity for coil collapse belong in three major categories:

- Material being processed — this includes chemical composition, incoming and final product dimensions.
- Rolling mill or other processing line — this includes configuration, equipment parameters and capabilities, quality of maintenance, characteristics and performance of control system including responsiveness to process variability.
- Process — this includes a set of processing parameters and their variability inherent for the given rolling mill or line, time-temperature-deformation routes, etc.

Normal stresses σ_n are dictated by tension applied during coiling, by pressure exerted by coiler wrapper rolls, and by mandrel expansion or contraction. During coiling, tension is applied between the last finishing stand and the coiler; when the pinch roll is engaged there is tension between the last finishing stand and the pinch roll, and between the pinch roll and the coiler. Wrap tightening and hence the magnitude of normal stresses can also be lowered by inner wrap movement due to the mandrel contraction during coiling (when the radial pressure is too high) or for coil removal.[2]

Shear stresses arise from tension variations that can be caused by mismatch between the strip speed out of the rolling stand and strip linear speed during coiling, especially in zooming mills. Gravitational forces due to large coil mass can also be a source of shear stresses. The latter can be amplified by poor strip flatness.

Strip speed mismatch can also be caused by volume changes induced by phase transformations during cooling, which are determined by chemical composition of steel, required rolling finishing and coiling temperature setpoints, runout table (ROT) cooling strategy, strip dimensions, and rolling/runout table speed profiles that define the time available for transformation. Besides phase transformation, the volume of the strip changes due to conventional thermal expansion or contraction during coiling. This can cause additional speed mismatch and may require speed synchronization and tension correction.

Low tension between the pinch roll and coiler at the beginning of coiling of head and tail end, strip poor flatness, and/or loss of tension due phase transformation at this stage can contribute to poor wrapping quality of extreme ends and to low rigidity of innermost wraps also leading to coil collapse.

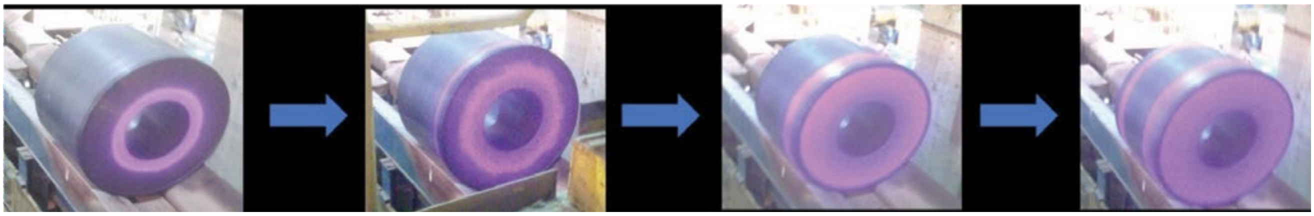
Significant variations in normal and tangential stresses during coiling can be brought about by coiler mandrel eccentricity. Big mandrel oscillations can substantially contribute to coil collapse. Besides, the capacity of the mandrel to expand during coiling must be ensured; sporadic cases of collapse have been correlated with limited mandrel expansion (either due to mechanical issues or inappropriate setup).

Thus, the magnitudes of normal and shear stresses during coiling are the functions of steel composition, strip dimensions, configuration of the rolling mill, cooling capacity, parameters of coilers and the responsiveness of the control system, as well as on the quality of maintenance.

Friction coefficient between the wraps is determined by the conditions of strip surface which in turn depend on surface scale (and hence on composition of steel), on the quality of descaling, both in roughing and finishing mills, on rolling lubricant that could be carried over, as well as on the cooling water both carried over from the runout table and applied during coiling. Variations in friction between the wraps can be significantly influenced by poor strip shape (flatness).

Figure 3

Progress of phase transformation in a coil. Transformation manifests itself by temperature increase due to latent heat release. The nonuniformity of transformation, temperature rebound and associated thermal expansion within the bulk of the coil are evident.



Role of Austenite Phase Transformation During Cooling

Phase transformation of austenite during cooling is one of the key players determining the propensity for coil collapse due to transformation-induced volume changes and the accompanying generation of latent heat. When austenite transforms during cooling, the volume of steel expands. The kinetics, magnitude and uniformity of volume expansion, as well as those of latent heat release and associated temperature recoalescence, are determined by steel composition, cooling requirements and pattern, time, location and type of transformation, coil mass, and coil cooling conditions. It is necessary to note that temperature recoalescence due to transformation can cause additional increase in volume because of thermal expansion, especially after the coiling has been completed (Fig. 3).

Three situations are possible during cooling after hot rolling:

1. Transformation and hence volume expansion occur entirely on the ROT. These volume changes are compensated by proper adjustment of tension and speed synchronization, the latent heat release is compensated by ROT cooling.
2. Austenite does not transform on the ROT; the volume of the strip decreases due to thermal contraction, and this is compensated by proper tension adjustment and synchronization of speed between the last finishing stand and coiler with account for mill acceleration. Phase transformation, the associated volume increase, latent heat release and volume expansion due to thermal expansion after transformation occur during coiling and coil cooling and are highly nonhomogeneous within the bulk of the coil (Fig. 3). The biggest amount of heat is released when austenite transforms into ferrite and pearlite; bainitic and martensitic transformations generate significantly smaller amounts of latent heat.
3. Only partial transformation takes place on the ROT. This is the most complicated situation, especially in zooming mills, when it is practically impossible to predict the extent of transformation and hence volume and temperature variations during cooling on the ROT and coil cooling, and to develop the proper tension and other means of compensation and synchronization.

For most carbon steel grades, when the coiling temperature (CT) is lower than the transformation temperature in cooling Ar_1 (end of austenite decomposition) for a given cooling rate and strategy, austenite transforms into ferrite or ferrite-pearlite mixture. As noted earlier, in this case the transformation is complete on the ROT, so the wraps of coils formed under such circumstances only experience thermal contraction in subsequent cooling. In alloyed compositions, austenite can also transform into bainite and martensite. Application of adequate cooling strategy can ensure the completion of austenite transformation on the ROT even in this case as well.

On the other hand, when a significant amount of austenite remains in steel at the coiler position, transformation-induced volume expansion, heat release and subsequent thermal contraction of transformation product phases take place in the coil during air cooling, resulting in significant looseness. The higher wrap looseness (lower circumferential tension) and lower mechanical strength are two contributing factors that make grades with a delayed phase transformation more susceptible to sag. Commonly, for specific grades, some extent of coil collapse can be observed immediately after extraction from coilers (even more evident when the handling operation is abrupt), and the shape continues to evolve to higher ovality during cooling in the yard.[1]

An additional complication that stems from phase transformation in coil cooling is that it takes place not simultaneously within the entire coil but progresses over time (Fig. 3). Nonuniformity of phase transformation is an additional source of tangential stresses that can change the relationship between normal and overall tangential stresses, ultimately leading to coil collapse. Nonuniform transformation cannot be controlled because of a large coil mass, significant thermal and cooling rate gradients within the coil, and also because no cooling agent

Table 1

Measures to Control Austenite Transformation on Runout Table

Parameter	Importance	Practice	Potential risks
Steel chemistry	High	Precise control and fine tuning of alloying and microalloying (C, N, Mn, Si, Nb, Al, B, Mo, ...) can be required for high strength grades	Mechanical properties of final products can be affected as they can fall below customer specs
Finishing delivery temperature (FDT)	High	Lower FDT is preferable for high strength steels; objective to obtain as much transformation on the runout table (ROT) as possible (especially for the head end)	▪ High forces and rolling instabilities can be induced in last stands when lighter gauges are rolled ▪ Strip shape issues ▪ Optimal FDT can be beyond mill capabilities
Rolling speed and acceleration	High	Lower speed and acceleration are preferable for high strength steels to allow more time for transformation on ROT	Slow rolling speed acceleration can result in unacceptable drop in FT, especially for thin gauges, induce rolling instabilities and shape issues
Descaling practice, delay table cooling practice	–	Earlier descaling is preferable, ensures better descaling in the finishing mill and hence high friction coefficient upon coiling	–
Roughing practice, transfer bar thickness-to-final thickness ratio (austenite conditioning)	Medium	–	–
Coiling temperature	Very high	Lower coiling temperature (CT) is beneficial for higher extent of transformation on ROT and/or transformation into bainite	▪ Low CT can be achieved with slow speed, cf. implications above ▪ Shape distortions are amplified at low CT ▪ Optimal CT may be beyond capabilities of the given ROT
ROT cooling strategy and profile; strongly depends on steel chemistry, hot strip mill configuration, ROT length and capabilities	Very high	Defines time – temperature ranges for transformation and strip shape quality: Must be selected as to maximize the extent of transformation on ROT without jeopardizing final mechanical properties of the product	Wrong cooling strategy can result in product rejection
ΔT = (FDT – CT); strongly depends on steel chemistry, hot strip mill configuration, ROT length and capabilities	High	Defines time – temperature ranges for phase transformation and strip shape quality: smaller ΔT is preferable for better shape	High ΔT can induce unacceptable shape distortions jeopardizing coiling quality and increasing propensity for coil sag
Head end shape out of finishing mill	High	As best as possible	–
Head end/tail end selective cooling for coiling temperature (extremity practice)	Very high	Cold head end is preferable Warm tail end	▪ Shape distortions of head end due to phase transformation at low temperature can jeopardize coiling quality ▪ High roll forces in cold rolling can be induced ▪ Special care must be taken if transformation occurs between pinch roll and coiler as it causes uncontrollable loss of tension due to strip expansion/elongation

is available for any type of control. Besides stimulating coil collapse, such transformation can induce various other adverse effects in downstream processing, final microstructure and properties of hot-rolled strips. Table 1 summarizes means to control phase transformation on the ROT and related risks.

Transformation of austenite into soft phases (ferrite, pearlite) can cause a drop in yield strength of steel during and after coiling. Yield strength drop during ROT cooling must be compensated by tension adjustment, otherwise it may result in strip necking and even strip breaks. Yield strength drop during coil cooling can lead to a decrease in σ_n and provoke coil collapse. Reduction of yield strength after coiling can also induce plastic deformation by creep due to large mass and can be aided by high bulk gravitational forces. On the other hand, transformation of austenite into hard phases (bainite and especially martensite) can cause yield strength increase and result in defects such as hot band edge cracking both on the ROT and during coil cooling.

Counteracting Coil Collapse

ArcelorMittal experience in controlling the ovality of hot-rolled coils can be categorized into two approaches: (1) mitigate and (2) deal with sagging phenomena. In the following paragraphs, the application of these two approaches is illustrated using data from three different ArcelorMittal hot strip mills "A", "B," and "C" located in Europe, South America and North America.

"First Approach": Mitigate Coil Sagging

The lower the transformation temperatures the higher the probability of having fractions of untransformed austenite at the coiler's position. The presence of some chemical elements[1,3–6] (such as C, Mn, N and B) and plastic deformation (austenite conditioning)[6] influence the austenite transformation kinetics. Physical simulations using Gleeble® Thermomechanical Simulators and dilatometers are efficient methods to assess austenite transformation temperatures as functions of cooling rate and deformation. Those findings usually reveal the potential options for optimizing the hot strip mill process to mitigate coil collapsing while honoring the mechanical properties required by customer specifications.

A combination of several mechanical, tribological and metallurgical factors makes the coil sag pattern not precisely predictable and quite challenging to solve. So far, besides the efforts to maximize austenite phase transformation in the ROT, steps have been taken toward optimizing coiling tension, coil weight[7,8] and storage conditions[1,8] (mitigating the effect of gravity by limiting the overload caused by multilayered coil stacking and encouraging the use of racks, that act as mechanical support).

In many ArcelorMittal plants, several countermeasures were implemented to produce critical materials, successfully mitigating the number of coils with severe collapse but with some undesired collateral effects and limitations. Increasing coiling tension is a frequently used practice but is limited by the power capacity of the coiler's mandrel and pinch roll. Racks with optimized support angles are used to counteract the effect of gravitational forces and creep on sagging. However, this strategy requires relatively fast and smooth transportation, preventing the coil from becoming too deformed before it is placed on a supporting rack. The coil weight limitation is a practice that affects the overall productivity of coil producers, the downstream operations and customer processing. Keeping a coil in the coiler with the mandrel expanded for some extra time after coiling is already completed is an abandoned practice due to its negative impact on the equipment lifetime.[1]

In addition to laboratory physical simulations, modeling simulations are powerful tools that can provide valuable information on the type and kinetics of austenite transformation under specific conditions. For this purpose, an ArcelorMittal R&D model was used, employing a large amount of data generated and collected at ArcelorMittal hot strip mills. The austenite fraction at the coiler position can be simulated for hypothetical scenarios, taking into account steel composition, ROT configuration and capacity (total length, water section length, cooling pattern, header position, and cooling

Figure 4

Industrial data showing the trend for coil collapse as a function of fraction of untransformed austenite at coiler position and strip thickness (represented by the diameter of each circle). Numbers inside circles indicate measured coil sagging in mm. The data obtained for a steel grade highly sensitive to coil sagging due to chemical composition (CT > Ar_1). Source: ArcelorMittal hot strip mill A.

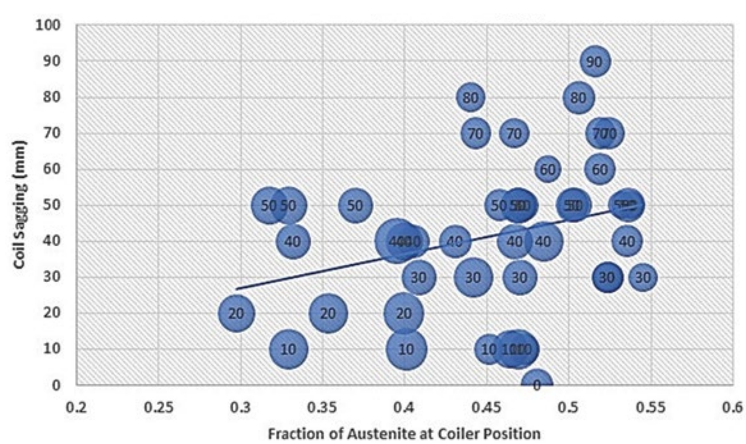


Figure 5

Effect of ROT parameters on untransformed austenite fraction at coiler position. FDT: strip temperature at the finishing mill exit; CT: coiling temperature; CP: cooling pattern. FDT and CT rated from 1 (minimum feasible) to 4 (maximum reasonable), according to mill capability and product requirements. Simulations valid for a steel grade susceptible to collapsing produced at ArcelorMittal hot strip mill B.

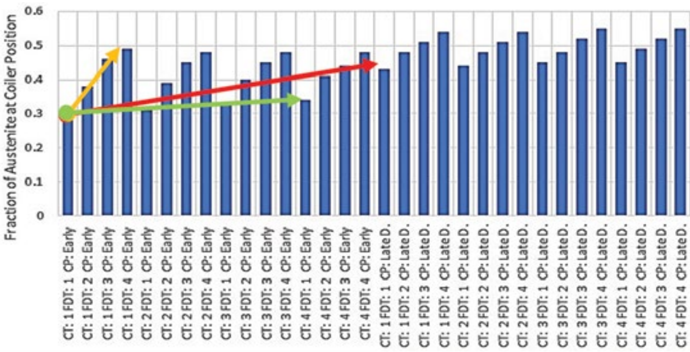
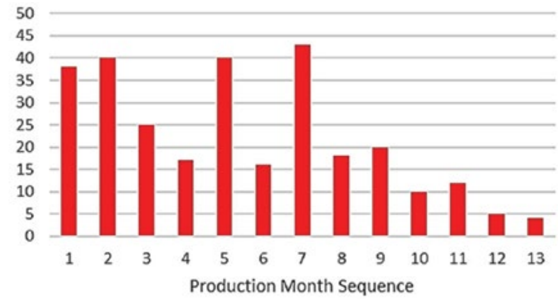


Figure 6

Impact of process intervention on the amount of coil collapsing. Data source: hot strip mill B.



capacity), strip temperature, deformation history (austenite conditioning), strip dimensions, and speed. Fig. 4 shows the calculated fraction of austenite untransformed on ROT (CT > Ar_1 > B_s) and how it contributes to collapse of individual coils hot rolled at ArcelorMittal hot strip mill A. As can be seen, the magnitude of collapse increases with a greater amount of austenite retained at the coiler position and thinner strip. That indicates that the measures aimed at increasing the extent of austenite transformation during ROT cooling should contribute to preserving coil rigidity and roundness.

Fig. 5 shows the transformation simulation results for ArcelorMittal hot strip mill B under two different cooling patterns (early quick and late cooling), and four different levels of finishing mill delivery temperature (FDT, finishing rolling temperature) and coiling temperature. FDT and CT levels increase from 1 to 4, that is, from the lowest feasible to the maximum reasonable value defined by mill capability and product requirements. It was found that the relevance to reduce the fraction of untransformed austenite for this grade follows this order: FDT (orange arrow), cooling pattern (red), and, with quite low impact, the coiling temperature (green). Based on the simulation results, industrial trials were run, and process modification were implemented progressively. A decrease in FDT implies a decrease in rolling speed for a given finishing mill entry temperature, transfer bar thickness (roughing practice) and final gauge. At a lower mill speed, more time is available for austenite to transform on the ROT before reaching the coilers, provided the condition (microstructure) of austenite does not change much with lower FDT. With that, the occurrences of coil collapse exceeding the acceptable limit dropped from 40% to 5% (Fig. 6). However, reducing rolling speed negatively impacts mill productivity (Fig. 7).

Figure 7

Decrease of finishing mill delivery temperature (FDT), mill speed, and productivity with respect to baseline (initial process setup). Data source: hot strip mill B.

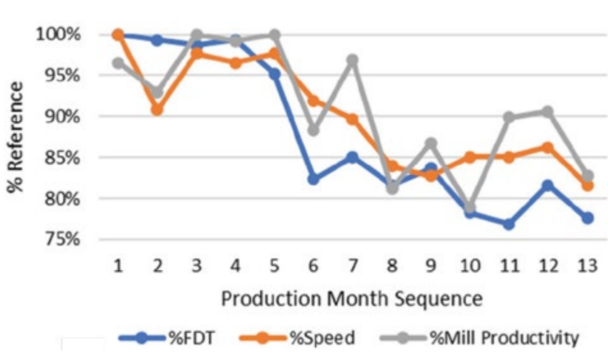


Figure 8

% production bottlenecked by a given equipment. With lower FDT and speed, the finishing mill (FM) became the productivity-limiting operation. Data source: hot strip mill B.

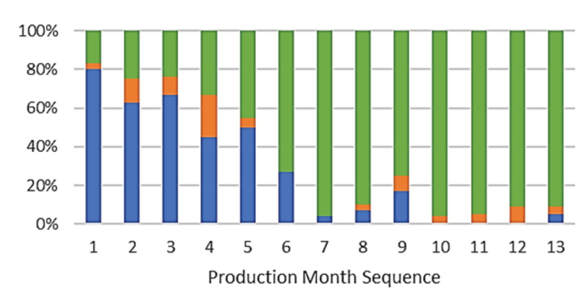
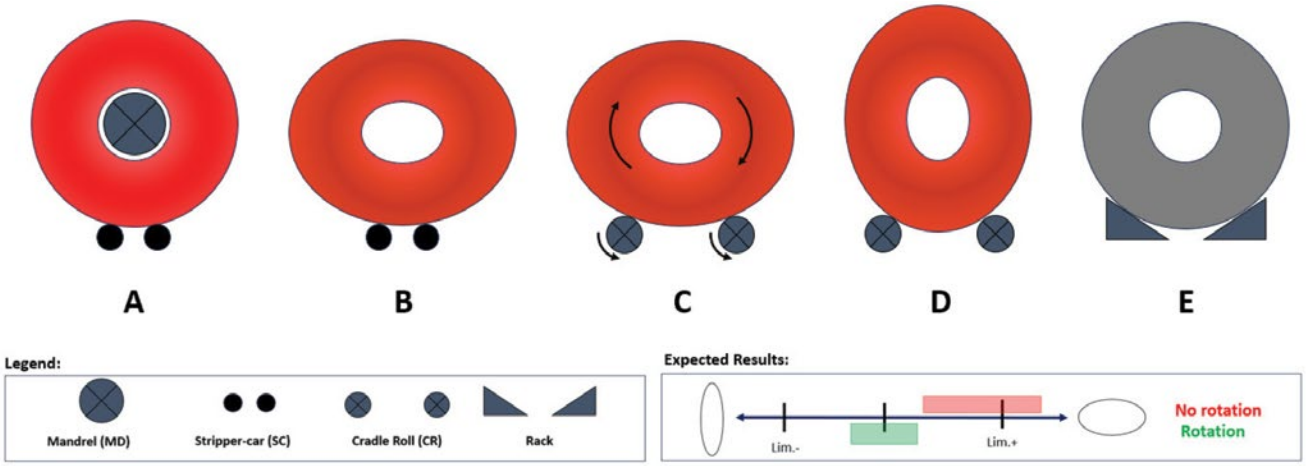


Figure 9

Schematic description of rotation device operation. The coil rotation mitigates the severity of coil sagging.



A) Coiling is finished, SC touches the coils. Phase transformation latent heat is released promoting dilatation.
B) MD is removed, the coil is moved out from the coiler. First signs of coil sagging become evident. Banding is applied.
C) Coil is transferred to CR. Rotation begins.
D) Rotation by 90° (or 270°) is completed. Collapsing is now canceling itself out.
E) The coil is transferred to the cooling yard and is placed on a rack. Coil sag is stabilized at acceptable level.

As FDT and mill speed are lowered, the finishing mill can become a productivity-limiting operation (Fig. 8). Besides, lowering FDT and rolling speed may change the transformation microstructure of the hot bands that can negatively impact the final properties of the products.

"Second Approach": Deal With Coil Sag

The new technology developed and patented by ArcelorMittal Global R&D East Chicago (patent # WO 2019 193 474) is based on offsetting the deformed shape of a coil by deformation in opposite direction. Once a coil removed from the coiler begins to exhibit ovalization, application of gravitational force in the direction normal

Figure 10

Cradle Rolls installed at hot strip mill C (2017–2018).

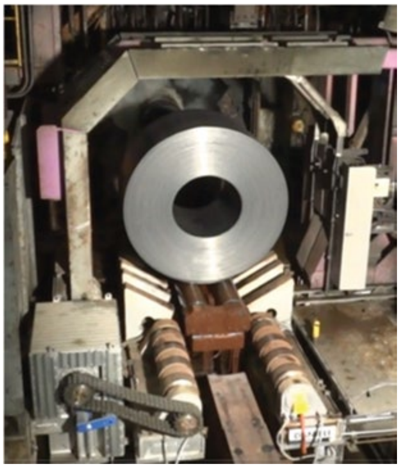


Figure 11

Overall result of different approaches to sagging control at hot strip mill C. For the same grade, the rate of coil sag above the acceptable limit (40 mm) was around 50%. Applying the "first approach" pushed values down to 15%. After commissioning of the rotation device technology the sag rate dropped to almost 0%.

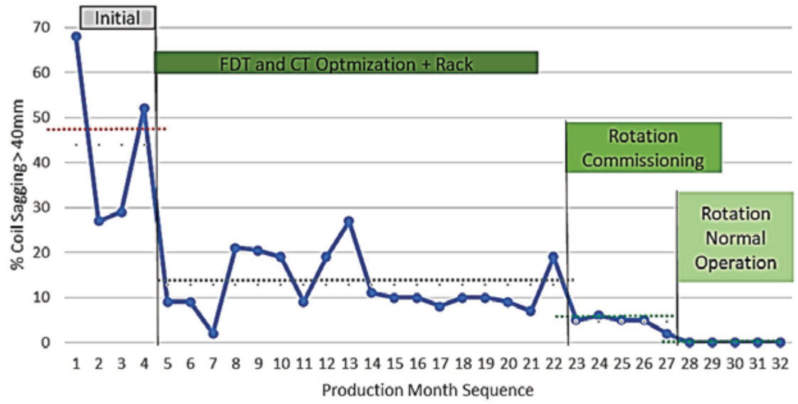
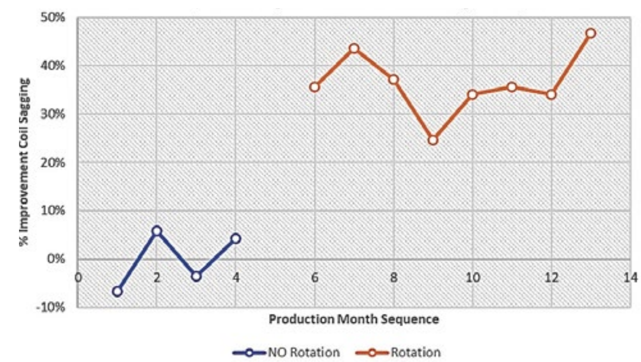


Figure 12

Coil sagging improvement for 2.8 mm hot: Coil sag for rotated coil: –25 mm, without rotation: +120 mm. Data source: hot strip mill C.

Figure 13

Coil sagging improvement for noncritical strip thickness (> 4 mm). Reduction in sagging rate is about 35%. Data source: hot strip mill C.



to the long axis of the coil can bring the coil shape back to circular. This can be done by simply rotating the coil 90° (or 270°); and the coil egg shape would make the eye even harder to deform. The coil is rotated by cradle rolls installed along the coil evacuation route. Fig. 9 explains the principle of the coil rotation device.

In the first ArcelorMittal plant to use this approach (hot strip mill C), the cradle rolls were installed in front of each of the three coilers just after the banding machines (Fig. 10). The rotation device was deployed after several "first approach" countermeasures to mitigate coil collapse (optimization of phase transformation combined with improvement of performance of mechanical equipment) had been applied. For the same grade, the initial rate of coil sag above the acceptable limit (40 mm) was around 50%; after applying the first approach techniques the collapse rate was reduced to 15%. The use of the rotation device technology dropped the collapse rate to almost 0% (Fig. 11).

It is commonly observed that coil collapse tends to be more severe for thinner gauges.[2,7,8] Application of coil rotation to most sag susceptible light-gauge (2.8 mm) alloyed steel grade at hot strip mill C resulted in a drop in collapse from +120 mm to –25 mm (Fig. 12). Even for less critical dimensions (thickness above 4 mm), for which the final coil shape normally complies with sagging tolerance, an improvement in sagging rate of around 35% was observed (Fig. 13).

The restrictions imposed by the first approach affect mill productivity (Figs. 6–8) due to lower rolling speed. To evaluate the potential for relieving mill speed restrictions, a trial was conducted at compact hot strip mill B with ROT length of 105 m and cooling section of 71.44 m. At the standard base rolling speed with no acceleration, the sag was +20 mm for a coil with a weight/cross-section ratio (WTW, factor contributing to coil collapse) of around 4.79 kg/mm^2. In the first trial, the speed was increased by 23%, causing a severe collapse of 69 mm that exceeded the quality limit. In the second trial, the speed was increased by mere 15%, resulting in the collapse of +40 mm. However, at 15% speed increase, with the use of the rotation device, the ovality was –15 mm, even for the highest WTW, which is the best value in the entire experiment (Fig. 14). The negative sign of the rotated coil collapse indicates that the vertical diameter is larger than the horizontal diameter. This rendered the possibility for mill speed increase as there would be more room to counteract coil collapse by rotation. In a similar

Figure 14

Utilization of the rotation device enables increase in mill speed while still complying with the quality requirements. Data source: hot strip mill B.

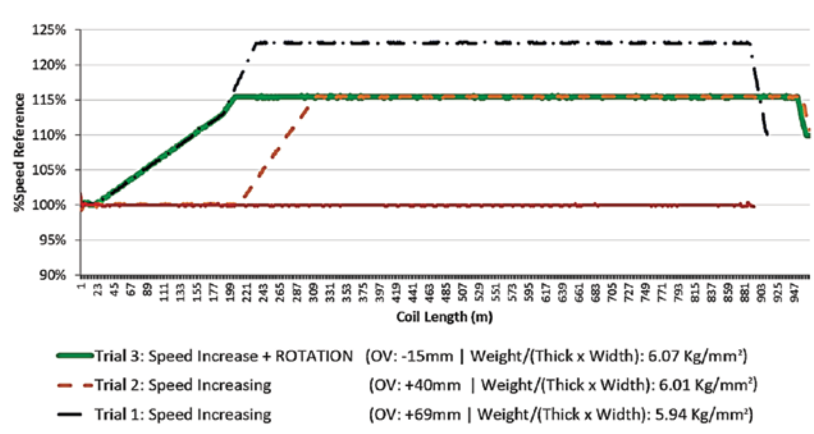
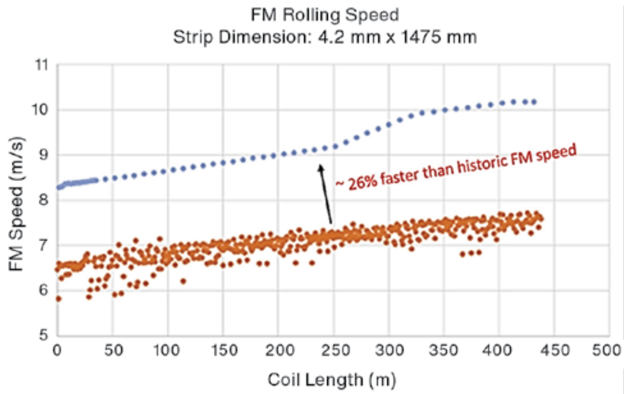


Figure 15

Trial performed at hot strip mill C on a 4.2-mm-thick coil showing the potential for 26% increase in rolling speed (blue dots) above the historical value (orange dots). In this trial, the final shape, finishing mill stability, and product quality were not compromised.



trial of 4.2 mm thick strip of the same steel grade at hot strip mill C the speed was increased by 26% without compromising the process stability and product quality (Fig. 15).

The concept of coil rotation moves the rolling speed threshold to a higher value, thus favoring productivity. This advantage is being progressively explored. Although in smaller quantities, there are still occasional cases of severe coil sagging, indicating that other factors need to be analyzed and better controlled in long production campaigns and the storage of hot-rolled coils. Efforts are being dedicated to improving the predictability of shape issues by establishing automatic measurement systems at strategic positions.

Utilization of coil rotation technology is quickly expanding within the corporation. It is already deployed at seven ArcelorMittal mills around the globe, contributing significantly to the achievement of production and quality goals.

Conclusions

Actions to promote phase transformation on ROT have been shown to mitigate coil sagging efficiently; still, they are insufficient to fully solve the problem for some critical grades with low transformation temperatures. Upon application of these countermeasures, the mill productivity is negatively impacted.

New technology invented and patented by ArcelorMittal Global R&D – East Chicago has brought additional progress and leveraged control to outstanding performance. This technology is spreading rapidly within ArcelorMittal plants, with seven hot strip mills already utilizing coil rotation devices.

The concept of coil rotation shifts the coil sag critical conditions for the hot strip mill process to more favorable ranges, thus enabling higher mill productivity.

The new technology created the value of US$59.13 million by reducing the rework and increasing mill productivity.

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