Investing in Excellence: Advanced Cold Rolling Technologies for Superior Electrical Steel Production

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ABSTRACT

The production of high-grade electrical steels, both non-grain oriented (NGO) and grain oriented (GO), is crucial for modern electrical applications, especially in the automotive and energy sectors. Primetals Technologies, the world leader in cold rolling of electrical steels, has developed technologies that enhance the production of these steels. This paper reviews trends in electrical steel production and highlights advanced cold rolling technologies for NGO and GO magnetic steels.

Traditionally, electrical steel was produced on reversing cold rolling mills using 20-high mills. The development of small diameter 6-high mills enabled the production of high-grade NGO steel and even high-permeability GO steel, depending on material strength and product thickness. The recent application of 6-high HYPER UC-MILL™ to tandem mills now allows efficient production of large quantities of electrical steel.

For high-efficient cold rolling of magnetic steels, key technologies include the HYPER UC-MILL with strip induction heating, Minimum Quantity Lubrication MQL™ for flexible and superb roll-gap lubrication and advanced strip temperature control. These technologies ensure stable, high-quality production of thin-gauge steels down to 0.2 mm or less. The advanced 6-high mill, with its small diameter work rolls, strip edge-oriented intermediate shifting and high torque transmission, achieves excellent thinness while maintaining strip thickness accuracy, flatness, and edge profile.

In producing thin-gauge, high-permeability GO electrical steels, the new split-housing 20-high HZ-Mill with double ASU flatness control stands out. This technology meets stringent requirements for dimensional accuracy and final magnetic properties, essential for high-efficiency electrical applications.

Primetals Technologies supports both traditional and new steel producers with its comprehensive cold rolling mill fleet and superior technologies. The company's extensive plant and process understanding, combined with the expertise of its customers and partners, enables the development of advanced electrical steel products.

The paper discusses the world's first twin-stand HYPER UC-MILL at thyssenkrupp Steel Europe (TKSE) in Bochum, Germany, and the world's first 6-stand HYPER UC-MILL continuous tandem cold mill at Shougang Qian'an in China.

Keywords: Cold Rolling – Reversing Mill – Tandem Mill – Ngo – Go – Hyper Uc-Mill – Minimum Quantity Lubrication Mql – Hz-Mill

INTRODUCTION

Electrical steel, a specialized steel tailored for its mechanical and magnetic properties, plays a crucial role in the energy transition and electromobility sectors. Its unique characteristics, such as high permeability, low core loss, and high electrical resistivity, make it indispensable in the manufacturing of transformers, motors, generators, and other electromagnetic devices. As the global demand for energy-efficient solutions and renewable energy sources continues to rise, the market for electrical steel is experiencing significant growth. This growth is mainly driven by the increasing complexity of electrical grids, the rise in electric vehicle (EV) production, and the expansion of renewable energy projects (e.g. wind power).

Fig. 1 illustrates the projected global EV sales, forecasting a 70% market share for electric vehicles and over 60 million new EVs sold per year by 2040. Modern electric vehicles, which can contain between 30 and over 100 electric motors, require approximately three times more electrical steel than traditional combustion engine cars. This significantly increases the demand for developing and producing electrical steel with superior magnetic properties.

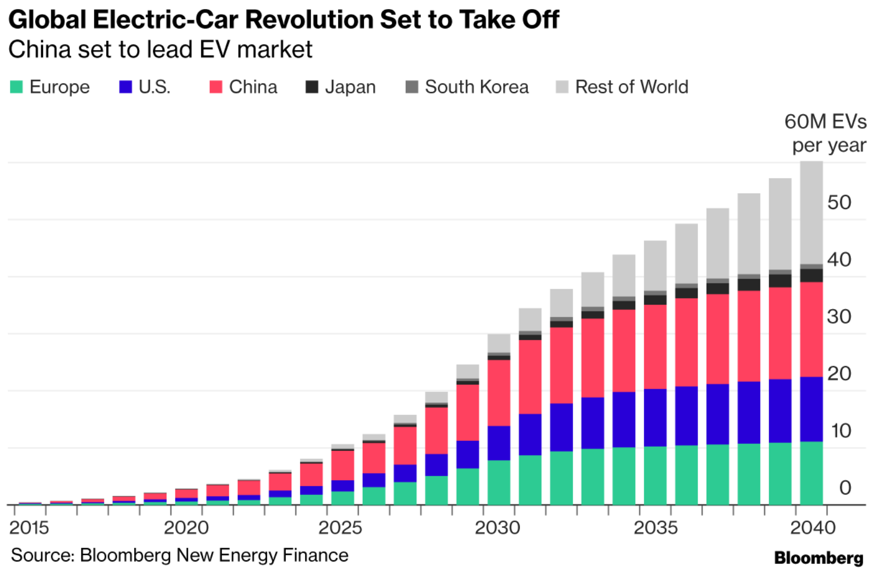

Figure 1. Forecasts of annually sold electric vehicles worldwide

Electrical steel can be categorized into grain-oriented (GO) and non-grain oriented (NGO) types. GO electrical steel exhibits anisotropic behavior, meaning its magnetic properties are optimized in one direction. GO electrical steel is primarily used in transformers due to its high efficiency in directing magnetic flux. In contrast, NGO electrical steel is utilized in rotating machinery such as motors and generators, where magnetic properties are required in multiple directions.

High-permeability electric steel is also essential for generators in wind turbines because it significantly reduces core losses and enhances the efficiency of energy conversion from mechanical to electrical energy, thereby optimizing the overall performance and reliability of the wind turbines.

Electrified Vehicles (EVs) call for lightweight steel body structures, high-efficiency electric traction motors, and advanced battery systems to maximize cruising distance. These features help reduce mass and greenhouse gas emissions over the vehicle's entire life cycle.

Recently, there is a sustainable demand from the automotive industry for ultra-thin non-grain oriented electrical steels with 3.2% to 3.6% silicon and in a thickness range of 0.2 mm to 0.3 mm. These grades, often referred to as NGO-EV, have stringent requirements concerning geometrical tolerances, surface quality, material strength, texture evolution, and magnetic properties.

CHALLENGES IN COLD ROLLING OF ELECTRICAL STEELS

Cold rolling is a critical process in the production of NGO and GO electrical steels, significantly influencing their final magnetic properties and mechanical performance. This process involves reducing the thickness of steel sheets by passing them through rollers at room or elevated temperature, which enhances the steel's strength and surface finish. Advanced cold rolling techniques, such as the 6-high HYPER UC-MILL or the 20-high HZ-Mill technologies, have been developed to meet the stringent requirements of high-grade electrical steels. This technology offers superior reduction and shape control capabilities, ensuring consistent quality and performance.

High-grade electrical steels are characterized by their hardness, brittleness, and thinness, which pose significant challenges during the cold rolling process. The brittleness, particularly at room temperature, and high rolling loads (strip tension, contact pressure, and shear stresses in the roll bite) increases the risk of strip breaks, which can lead to equipment damage and production delays.

In addition to the challenging production conditions, maintaining product quality in terms of thickness, flatness, edge drop and surface finish is of paramount importance. Tolerances for these criteria are constantly tightening, especially as the target delivery thicknesses approach 0.2 mm and below. Maximizing yield must be balanced with the efficient use of process consumables. These requirements impact the mechanical, electrical, and process design of the cold rolling mills.

2-Stand Reversing Mill for Cold Rolling of Electrical Steel

In 2023, Primetals Technologies delivered the world's first 2-stand HYPER UCM™ reversing cold rolling mill to thyssenkrupp Steel Bochum. This new flagship cold mill is dedicated to producing high-grade electrical steel and advanced high-strength steels, with an impressive annual production capacity of 475,000 tons (see Fig. 2).

With its back-and-forth (reversing) operation, the double reversing mill can roll particularly thin strip with an end-product thickness down to 0.2 millimeters. Featuring a highly versatile mill concept, the plant is, on the other hand, also capable of handling heavier gauges i.e., products that meet the highest-possible strength requirements. Highly skilled operators supported by advanced automation solutions are the driving force behind achieving these extraordinary strip dimensions. The need for advanced high-strength steel grades used in electrical vehicles is projected to rise to extremely high levels over the coming decades. This mill ensures that thyssenkrupp Steel is well-prepared to deliver thinner and lighter steel of very high quality – exactly the type of steel needed in electrical vehicles.

Several factors contributed to thyssenkrupp Steel's decision to select Primetals Technologies as its supplier, one of them being strong references. Primetals Technologies is the market leader in cold rolling solutions to produce silicon steel, with a 90 percent market share worldwide. Another important factor is the unique features of HYPER UCM technology. With this solution, it is possible for operators to influence the edges of the strip – the most common area for cracks – in a very flexible way.

The reversing mill features a twin-stand 6-high HYPER UC-MILL with driven work rolls and new MH-spindles for the highest torque transmission. The mill is equipped with Minimum Quantity Lubrication MQL and an inductive strip heating system, dedicated to producing non-grain oriented (NGO) electrical steel and advanced high-strength steels (AHSS).

Investing in two twin-stand reversing mills provides several advantages over a continuous tandem mill, including lower initial capital expenditure (CAPEX), a smaller footprint, and increased availability.

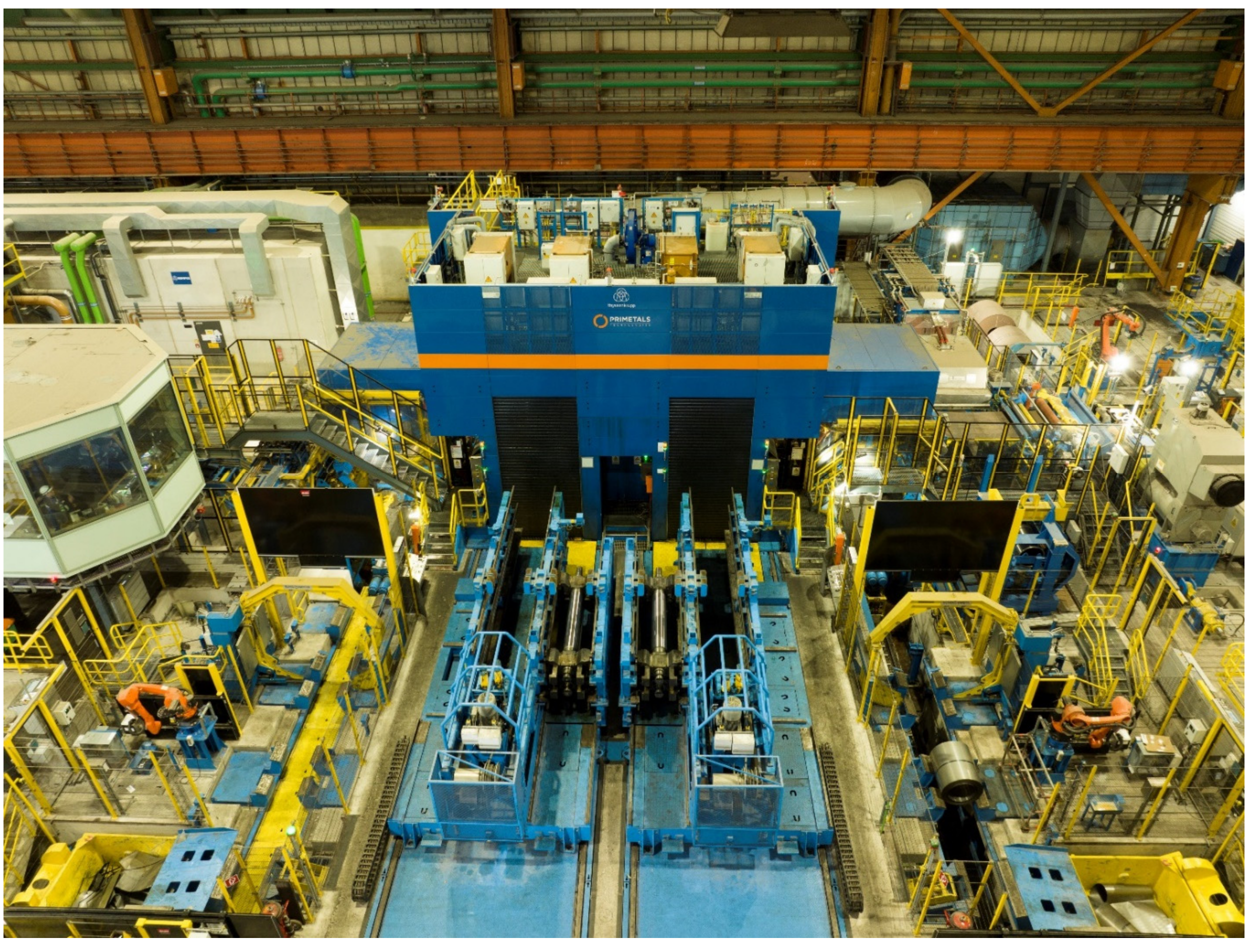

Figure 2. Double cold reversing mill

The World’s First 6-Stand Tandem Cold Mill for Cold Rolling of Electrical Steel
The world's first 6-stand continuous tandem Cold Mill, equipped with HYPER UC-MILLs in all stands, marks the beginning of a new era in the cold rolling of electrical steel. Fig. 3 shows a typical configuration of 6-stand tandem cold rolling mill for electrical steel.

Primetals Technologies has supplied a 6-stand HYPER UC-MILL to Shougang Zhixin Qian’an Electromagnetic Material Co., Ltd. (Shougang Qian’an). This installation enabling the production of harder and thinner materials with enhanced quality. With this new tandem cold mill, Shougang Qian’an is well-positioned to meet the growing demand for electrical steels, ensuring they can supply high-quality materials to their customers efficiently and effectively.

Shougang Qian’an is part of the Shougang Group Co., Ltd. Previous projects of Primetals with Shougang included the supply of four 20-high HZ-mills for the production of high permeability grain-oriented (HGO) steel and a PL-TCM for the production of non-grain oriented (NGO) steel grades.

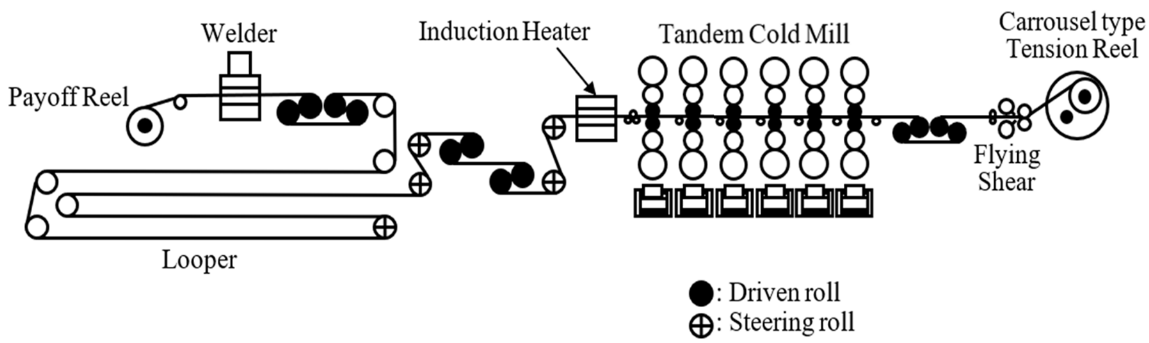

Figure 3. Typical configuration of continuous 6-stand tandem cold rolling mill

A standout feature of this advanced 6-high tandem cold mill is its additional work roll shifting function (cf. Fig. 4), which allows for precise edge profile control of electrical steels. This capability is essential for maintaining high-quality standards in the production of thin-gauge electrical steels.

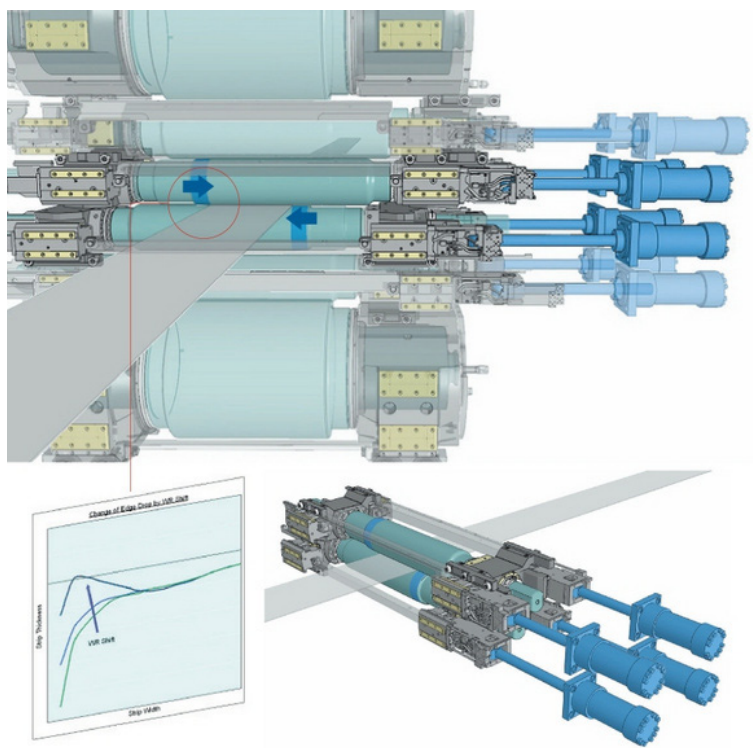

Figure 4. Additional work roll shifting for optimized edge drop

The new HYPER UCM tandem mill is designed to cold-roll harder and thinner materials with high quality and productivity by utilizing smaller work rolls driven by a work roll drive system. It produces electrical steel grades, advanced high-strength steel (AHSS) grades, tin grades, and more, with thicknesses ranging from 0.18 to 2.5 mm and widths between 750 and 1,320 mm.

HYPER UC-MILL and Strip Edge-Oriented Roll Shifting

The 6-high HYPER Universal Crown Mill (HYPER UCM [2], cf. Fig. 5) process represents a significant advancement in the production of electrical steel. The work roll diameter of a HYPER UCM, ranging from 300 to 340 mm, is widely used for electrical steel production. It features driven work rolls and an axially shiftable intermediate roll that adjusts according to the actual strip width, along with an installed work roll and intermediate roll bending system. This setup allows for the use of a cylindrical work roll shape to achieve a stable strip shape, meeting the highest strip flatness requirements.

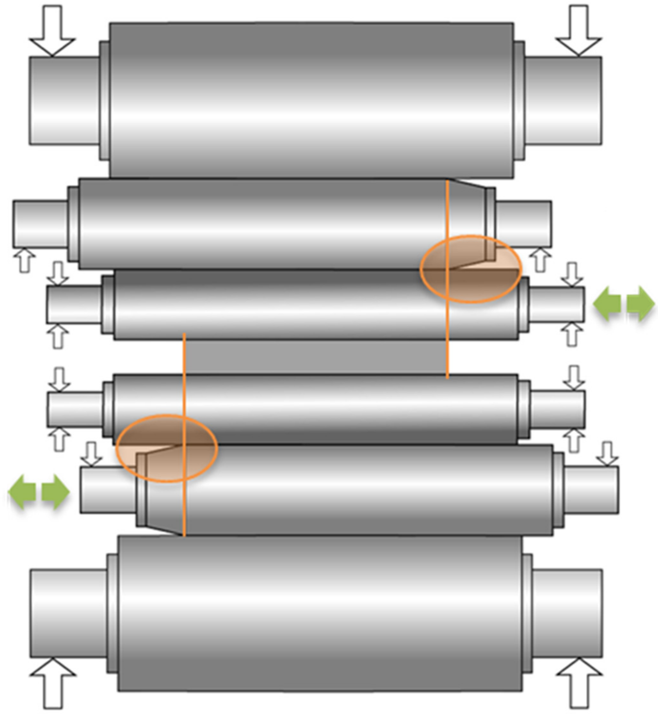

Figure 5. Core design of a 6-high HYPER UCM

Figures 6 and 7 illustrate the advantages of a HYPER UCM, which eliminates undesired contact areas (cf. Fig. 7 left) thanks to the tapered work roll design and smart edge-oriented intermediate roll shifting. This design enables excellent shape controllability.

For cold rolling of hard materials, the strip thickness profile decreases sharply at the edges, a phenomenon known as edge drop. This occurs due to longitudinal deviations in the work roll flattening. Minimizing edge drop is particularly crucial in the production of electrical steel, as it is essential for achieving high lamination factors and consequently low core losses.

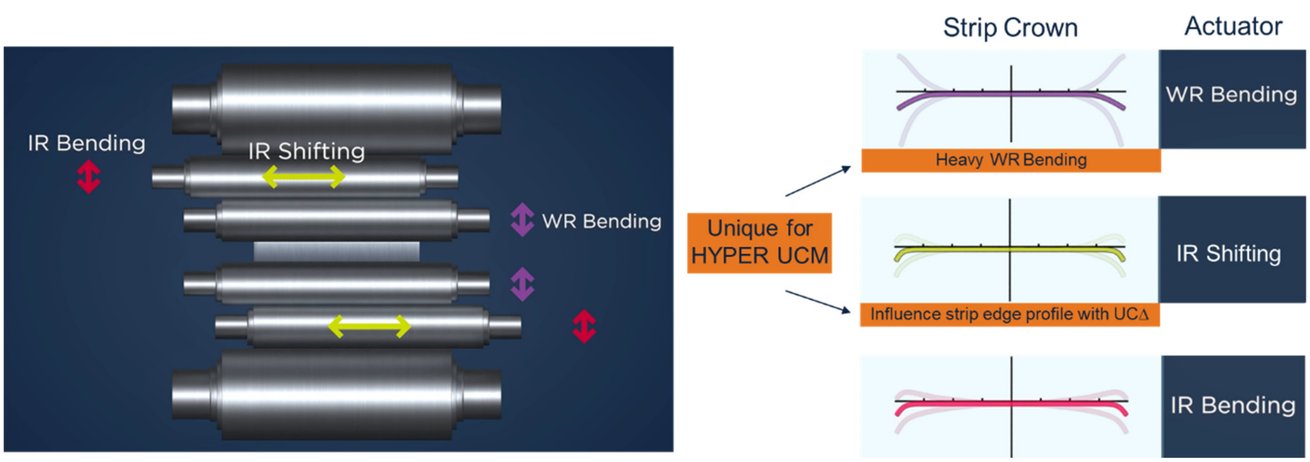

Figure 6. Various flatness actuators of the HYPER UC-MILL

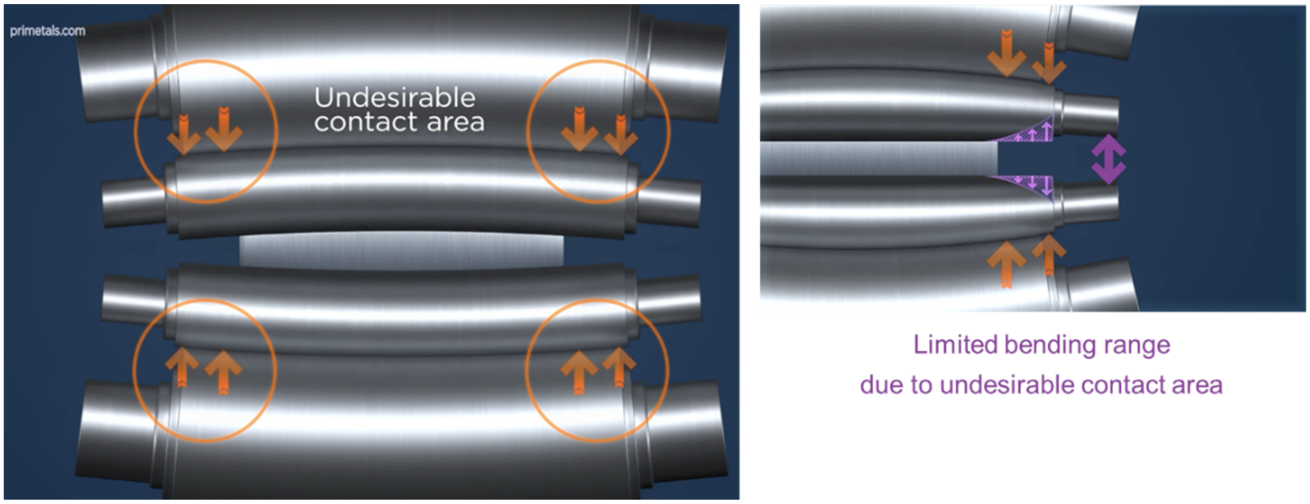

Figure 7. 4-high mill with undesirable contact area and limited positive work roll bending range

The most effective mill stand technology for producing high-grade NGO electrical steel is the 6-high Hyper Universal Crown Control Mill, an advancement of the well-established UCM technology. To utilize smaller diameter work rolls, a comprehensive study was conducted on the influence of work roll diameter on shape control capability, Hertzian stress between rolls, and the reduction ratio. The study found that using smaller diameter work rolls reduces rolling loads and allows for higher reduction ratios. The optimal reduction ratio was achieved with work rolls approximately 20-40% smaller in diameter than those of the standard UCMILL^{TM}.

However, decreasing the work roll diameter necessitated increasing the intermediate roll diameter to maintain mill stability and ensure optimal shape controllability. Additionally, a new gear-type spindle, known as the "MH-Spindle," was developed to transmit higher torque with small diameter work rolls. This technology can transmit 2.7 times the torque of a conventional Universal Joint (UJ)-type spindle (cf. Fig. 8).

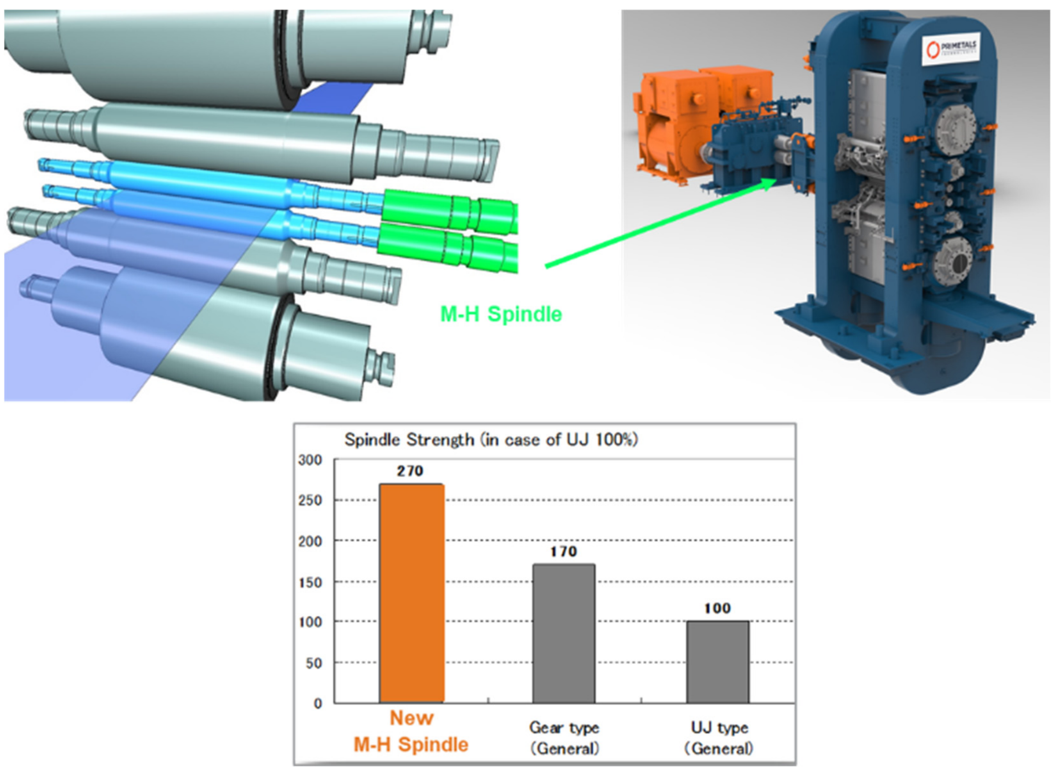

Figure 8. New MH-Spindle of HYPER UC-MILL

As a result, the HYPER UC-MILL was introduced as a new type of rolling mill, utilizing smaller work rolls and high-strength spindles. This design enables the rolling of high-strength materials and high-grade electrical steels.

Advanced Split Housing Type 20-High Mill
For heavy reduction cold rolling of harder and fragile materials such as grain-oriented (GO) or high-grade non-grain oriented (NGO) electrical steel, an advanced 20-high cluster mill can be applied. Modern 20-high high reduction mills feature a split inner housing, replacing the conventional large-scale mono-block type 20-high ZR. This design allows for precise control and handling of ultra-thin, hard, and brittle materials while maintaining the highest product quality and geometrical tolerances.

Advanced 20-high cluster mills (cf. Fig. 10) have ultra-small diameter work rolls (2 rolls, e.g. Ø80 mm) which are supported by the first intermediate rolls (IMR; 4 rolls), second IMR (6 rolls) and segmented backing bearing shafts (8 shafts). The inner housing which supports these rolls is divided into top and bottom sections and is supported by the operation (OP) side and drive (DR) side outer housings via the pass line adjusting device on the upper side and the OP side and DR side push-up cylinders on the lower side. A wedge and stepped rocker plates type pass line adjustment device compensates changes in the diameter of the upper roll group. A load cell is also installed, which ensures highly accurate measurement of the rolling load. High response servo valves are typically mounted directly on both push-up cylinders.

The 20-high HZ-Mill from Primetals Technologies is an advanced split-housing Sendzimir mill designed for producing high-permeability GO and NGO electrical steels (see Fig. 9 and 10). This proven mill features several key technologies that ensure high dimensional accuracy and excellent magnetic properties, which are essential for high-efficiency electrical applications.

Figure 9: Advanced split-housing 20-high HZ-Mill

Primetals Technologies' HZ-Mill is specifically designed for the efficient rolling of hard materials such as electrical steel or stainless steel.

One of the standout features of the HZ-Mill is its double ASU flatness control system, which provides superior shape control during the rolling process. This system helps maintain the desired strip thickness, flatness, and edge profile, ensuring high-quality production of thin-gauge steels down to 0.15 mm or less.

In the HZ-Mill, workability is improved by increasing the roll clearance between the work rolls. The mill structure was optimized to secure the rigidity which is necessary in a rolling mill of this type. The housing is split into an upper and lower section to create a large gap between the upper and lower work rolls for easy threading and strip removing in case of cobbles and small bristles. In addition, in the split housing type, a high response hydraulic screw-down system and an advanced shape control mechanism are incorporated by utilizing the high rigidity and features of this structure.

Additionally, the HZ-Mill utilizes ultra-small diameter work rolls supported by intermediate rolls and segmented backing bearing shafts. This configuration ensures highly accurate measurement of the rolling load and enhances the mill's ability to handle ultra-thin, hard, and brittle material grades while maintaining the highest geometrical tolerances and product quality.

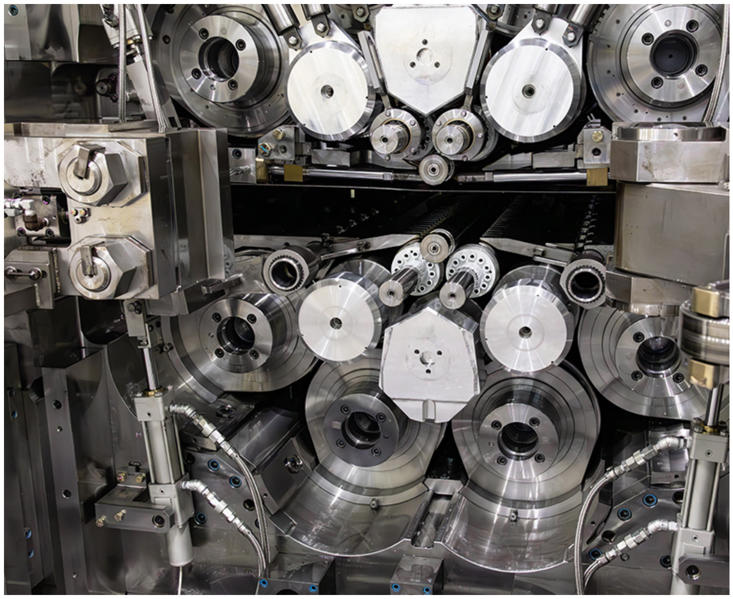

Figure 10: Mill front view and inner housing of a modern 20-high mill

Strip Heating Prior to Cold Rolling
Cold rolling of high-silicon electrical steel (Si ≥ 2.5%) is characterized by an increased risk of strip breaks due to the high brittleness of high-Si steels at typical cold rolling temperatures. This brittleness, combined with high rolling loads (strip tension, contact pressure, and shear stresses in the roll bite), can lead to the generation and growth of edge cracks, resulting in strip breaks and significant production downtimes and delays.

It is known that increasing the strip temperature before cold rolling can significantly reduce material brittleness (cf. e.g. [1]). During the first pass of a reversing mill, the strip temperature is typically at room temperature (e.g., 20 to 30°C). The room temperature brittleness also depends on the silicon and aluminum content of the strip material. Higher Si-content (≥ 2.5%) and Al-content (≥ 0.5%) can increase room temperature brittleness, reducing ductility and formability during cold rolling. Edge cracks are caused by prevented dislocation sliding, which leads to an unwanted twinning effect of the metal structure under applied rolling loads.

Induction heating (cf. Fig. 11) provides precise and uniform heating of the steel strip, which is crucial for maintaining the desired temperature range. This helps minimizing and eliminating issues like edge cracks and strip breaks when the strip is too cool.

Figure 11. Strip Induction Heater

Strip Temperature Prediction and Guidance
Strip temperature plays a crucial role in the stable and successful production of high-permeability electrical steels, especially during threading and the first pass rolling. An increased strip temperature can also be beneficial for the second and subsequent rolling passes. This can be achieved through controlled strip temperature management throughout the entire cold rolling process. If the strip temperature drops too low, the material's brittleness, combined with the applied rolling loads, may result in edge cracks and strip breaks. Conversely, excessively high strip temperatures can lead to increased work roll temperatures

and reduced hardness of the work roll shell material, potentially causing heat streaks, emulsion stains or other surface defects. Minimum Quantity Lubrication (MQL^{TM}, cf. [3]) can prevent the undesired strip temperature drop (cf. Fig. 12 without applied MQL) before the first pass. Entry side lubrication is performed with pure rolling oil atomized with air and sprayed directly onto the surface of the work rolls. This ensures that the strip temperature is not affected by roll-gap lubrication, as is the case with conventional recirculation emulsion lubrication.

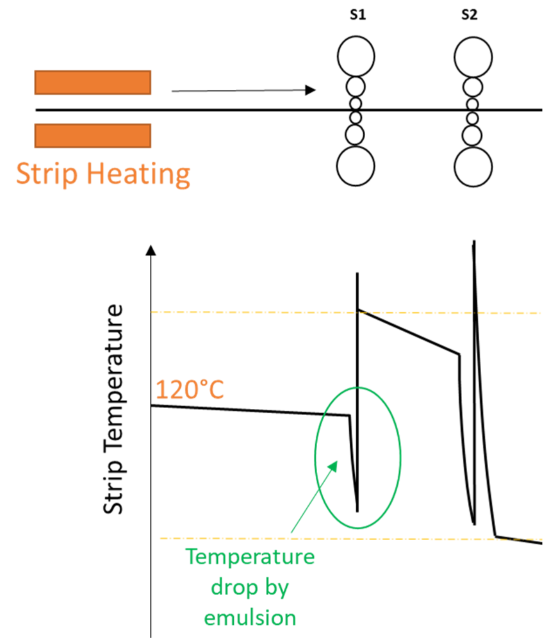

Figure 12. Example of strip temperature evolution in a double reversing mill with first pass strip heating without MQL

CONCLUSIONS

The development and integration of various innovations into advanced 6-high and 20-high reversing mills, as well as 6-high tandem cold rolling mills, have significantly enhanced the production and productivity of high-quality, thin-gauge non-grain oriented (NGO) and grain-oriented (GO) electrical steels. These advancements demonstrate that incorporating innovative technologies such as the HZ-Mill, HYPER UC-MILL, Minimum Quantity Lubrication (MQL), and strip induction heating, along with advanced automation solutions, has led to substantial improvements in productivity, minimum achievable product thickness, and overall product quality.

The HYPER UC-MILL technology, with its superior reduction capabilities and edge and shape control, has proven highly effective in meeting the stringent requirements of high-grade electrical steels. The use of smaller diameter and still driven work rolls, combined with an advanced edge-oriented roll shifting mechanism, enables precise control over strip shape and thickness, minimizing edge drop and ensuring excellent flatness. This is particularly beneficial for producing ultra-thin NGO-EV grades, which are critical for the automotive industry's demand for lightweight and high-efficiency electric traction motors.

For grain-oriented (GO) production, the newly developed 20-high HZ-mills incorporate advanced features to handle ultra-thin, hard, and brittle material grades while maintaining the highest geometrical tolerances and product quality.

The implementation of strip induction heating has addressed the challenges associated with the brittleness of high-silicon electrical steels at room temperature. By precisely controlling the strip temperature, the risk of edge cracks and strip breaks has been significantly reduced, leading to more stable and efficient production processes. The combination of induction heating and Minimum Quantity Lubrication (MQL) has further optimized rolling conditions, maintained the desired strip temperature, and enhanced lubrication, which is crucial for achieving high-quality surface finishes and reducing rolling loads.

Advanced automation solutions for reversing and tandem cold mills are crucial for producing high-quality electrical steels. These solutions include sophisticated thickness and flatness control modules, feedback control based on internal model control, and roll and coil eccentricity compensation to ensure tight tolerances and smooth rolling processes, ultimately enhancing the final product's quality.

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