COLD ROLLING SOLUTIONS FOR THE PRODUCTION OF AHSS / UHSS AND HIGH-SI ELECTRICAL STEEL

Konrad Krimpelstätter[1]
Ichiro Maeno[2]
Gerhard Finstermann[3]
Hironori Shimogama[4]
Takehiko Saito[5]

Abstract

Automobile manufacturers are developing Electrified Vehicles with light steel body structure designs that reduce mass and therefore greenhouse gas emissions over the vehicle's entire life cycle. This raises the demand for the production and development of Advanced and Ultra High-Strength Steels (AHSS / UHSS) and Electrical Steels with increased permeability and reduced core loss to improve energy conversion efficiency.

To meet this requirements the steel market is tending towards new generations of AHSS with improved formability (3rd generation AHSS) and high-silicon steels with higher strength and thinner products. With this growing demand for advanced high-strength steels and electrical steels, producers are faced with a unique and interesting challenge in producing materials that strain or exceed the capabilities of existing mill equipment and automation designed to produce low- to medium-carbon sheet. While specialty steel producers have known for decades how to process special high-strength steels and thinner gauges, this equipment typically does not offer the yield and productivity desired by the market, necessitating innovation in re-engineering existing equipment to meet the market demands more economically than new construction. In the case of cold rolling, this can be supported through variable roll geometries, more effective roll-gap lubrication technologies, application of strip heaters (Warm Rolling) to reduce risk for edge crack propagation and strip breaks as well as continuous rolling managed by state-of-the-art automation technologies.

Keywords: Advanced high-strength steels, AHSS, Third Generation AHSS, Ultra high-strength steels, UHSS, Electrical Steel, Silicon Steel, thin gauges, cold rolling, roll-gap lubrication, mill chatter

[1] *Dr., Head of Technology & Innovation Hot and Cold Rolling Mills, Primetals Technologies Austria GmbH, Linz, Austria*

[2] *Senior Vice President, Head of Rolling & Processing Europe, Primetals Technologies Austria GmbH, Linz, Austria*

[3] *Dr., Vice President and Head of Technical Sales Cold Rolling Mills, Primetals Technologies Austria GmbH, Linz, Austria*

[4] *Vice President and Head of Technical Sales and Project Management Cold Rolling Mills, Primetals Technologies Japan Ltd., Hiroshima, Japan*

[5] *Dr., Innovation Manager for Cold Rolling and Processing, Primetals Technologies Japan Ltd., Hiroshima Japan*

1. INTRODUCTION

Today the trend to use silicon steels in electrical appliances or advanced and ultra high-strength steel grades (AHSS / UHSS), such as dual phase or press hardening steels in the automotive industries, motivates steel producers to invest in rolling mill equipment and automation solutions to modernize their existing production facilities.
In order to meet or even surpass today's product quality levels, knowledge of the processes as well as the devices, machines and plants comprising these processes is essential.
The majority of global high-strength steels is cold rolled using coupled pickling line tandem cold mills (PL-TCM) or continuous tandem cold mills (TCM). Since the onset of the use of high-strength steels, tandem cold mills have seen continuous design improvements to include the processing of much harder materials, such as DP/MP steels, stainless steel, silicon steel and tin-plate, along with the existing conventional carbon steels. While processing harder materials is a must, product quality (thickness, flatness and surface) is still of paramount importance. Tolerances for these criteria are constantly tightening, especially as the target delivery thicknesses dive below 0.2 mm. Maximization of yield must go hand-in-hand with efficient use of process consumables. These requirements affect the mechanical, electrical and process design of the mills. The mechanical rolling capability of a given mill is primarily determined by:

- Power of the main motors
- Available roll separating force (RSF)
- Mill stand stiffness
- Shape control capability
- Work roll diameter
- Roll-gap lubrication efficiency

2. INFLUENCE OF WORK ROLL DIAMETER

The effect of the work roll diameter is schematically demonstrated in Figure 1, where the specific rolling force for a certain material strength and fixed strip thickness reduction as a function of the strip exit thickness is shown.

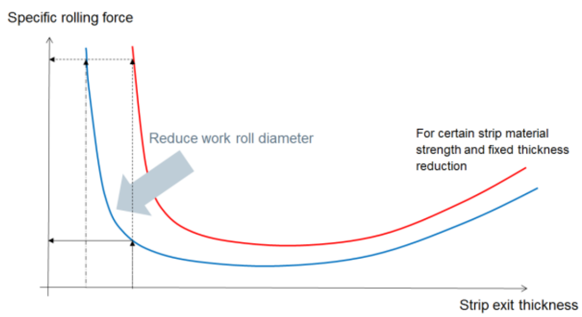


Figure 1. Specific rolling force as a function of strip exit thickness and work roll diameter.

The rapid increase of specific rolling force at thinner exit thickness results from severe work roll flattening. The additional required energy transferred via the roll load cylinders is mainly waste into elastic deformation of the work rolls. As can be seen from this graph, reducing the work roll diameter (i.e. switching from red to blue curve in Figure 1) decreases the required specific rolling force to achieve a certain product thickness, mainly as a result of decreased work roll flattening. This in turn allows for the production of lower strip exit thickness at comparable rolling force levels. This phenomenon has been successfully utilized in cluster mills, as 20-high mills or Z-mills, to be able to produce stainless steel and special grades for many years. For the sake of completeness it needs to be added that a further limitation of final gauge can arise due to “kissing rolls” outside the strip width.

3. FLEX-HI MILL

In order to meet current and future requirements of mill operators of conventional tandem mills and reversing mills, a new development allows for a significant extension of the cold rolling capabilities of existing 4-high mills with only minor modifications to the installed equipment. This new mill technology called Flex-HI has the ability to operate individual stands either as a 4-high mill with large work rolls or as an 18-high mill with small work rolls and thus utilizing the above described potential. By means of quickly interchangeable cassettes (cf. Figure 2), Flex-HI keeps high productivity for soft to medium strength materials in 4-high mode, and allows steel producers to extend their product mix with new generations of high-strength steels in 18-high mode. The system allows for changing the whole 18-high insert or only the work rolls, depending on the process and product requirements.

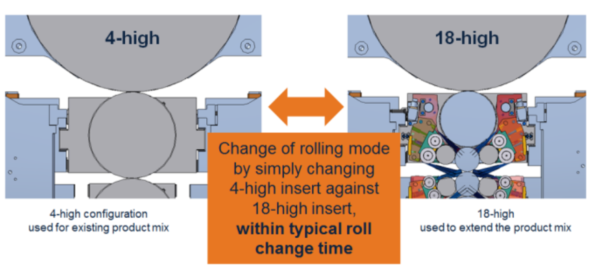


Figure 2. Flex-HI mill concept.

The 18-high insert, which has top and bottom assemblies, consists basically of the driven intermediate rolls, small work rolls and lateral side support rolls on either side of the work roll (see Figure 3). Intermediate roll chocks with bearings serve to guide the intermediate rolls and to transfer the bending force to the intermediate rolls. The work rolls perform the reduction of the incoming strip to the target thickness by transferring the roll force and drive torque to the strip.

Side support arms, which are mounted to the intermediate roll chocks, carry the lateral side support rolls and support rollers. The side support arms together with the support rolls are used to stabilize the work rolls in horizontal direction. For efficient cooling and lubrication, the side support arms are additionally equipped with nozzles (patented system).

By use of a lateral support mechanism integrated in the rolling mill stand, horizontal forces are guided from the support beam into the mill housings. Furthermore, the support mechanism compensates the grinding range of all Flex-HI insert rolls and adjusts the necessary work roll offset.

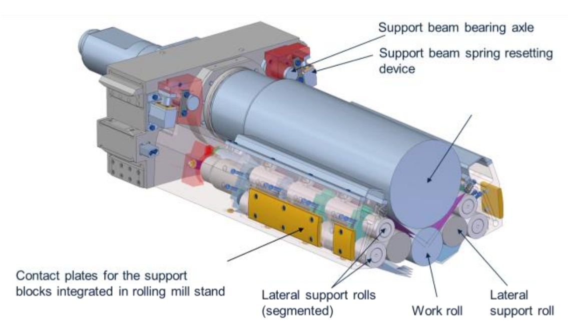


Figure 3. Flex-HI design of upper 18-high insert.

In a tandem mill, preferably the middle mill stands can be effectively equipped

with a Flex-HI system, e.g. mill stand 2, 3 and 4 of a 5-stand tandem cold rolling mill. Especially in mill stand 3 and 4, the reduction capability in 18-high mode compared to 4-high is significantly increased since the incoming strip into these mill stands is already hard (due to work hardening) and thin (due to reduction passes on first stands).
Figure 4 shows an example of the benefits of the 18-high mode to process high-Si electrical steel with hot strip dimensions 2.0x1400 mm. In classical 4-high mode operation, with work roll diameter of app. 460 mm, the achievable product thickness is app. 0.35 mm (app. 17.4 MN roll separating force in this case). A simple mode change in mill stand 4 from 4-high to 18-high mode with a work roll diameter of 180 mm, allows reducing the achievable product thickness down to 0.2 mm at significant lower rolling force levels (app. 8 MN roll separating force on Flex-HI stand).

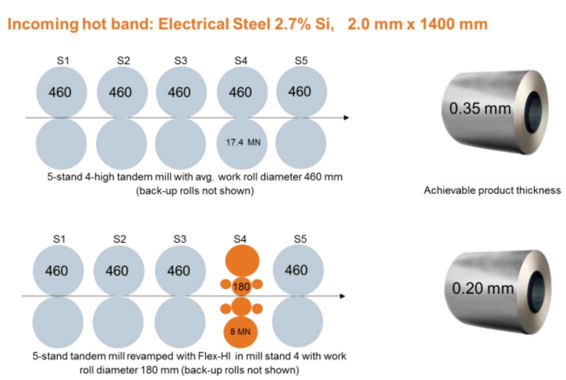


Figure 4. 5-stand tandem mill revamped with Flex-HI in mill stand 4.

The main focus of this innovation is clearly dedicated to the revamp of existing 4-high reversing and tandem cold rolling mills. Nevertheless, for new reversing mill installations, this technology also represents a serious alternative to cluster mills with the advantage of processing not only harder materials but also soft to medium strength steels competitively and with high productivity.

4. UCM-MILL AND STRIP EDGE PROFILE CONTROL

The work roll diameter of UCM-Mill (Universal Crown Mill) in range of 385 to 425 mm is widely used for electrical steel production in tandem cold mill configuration. It is characterized by driven work rolls and an axially shiftable intermediate roll according to the actual strip width, together with the installed work roll and intermediate roll bending system.
It is possible to utilize a cylindrical work roll shape (universal crown) to achieve a stable strip shape which meets highest strip flatness requirements.
In this configuration, edge profile control has become popular solution to improve yield loss especially in the electrical steel production as shown in Figure 5. For rolling of the hard electrical steel material, the thickness decreases sharply at the edge area. This is called edge drop and caused by longitudinal deviation of the work roll flattening. Especially for electrical steel rolling, less edge drop is essential. To reduce the edge drop, UCMW Mill, which has additionally a work roll shift mechanism is applied to the UCM Mill.

Work rolls are shifted by means of hydraulic cylinders provided in each shifting blocks at the drive side. Optimum roll gap profile is achieved by combining work roll shifting, intermediate roll shifting, work roll bending and intermediate roll bending.

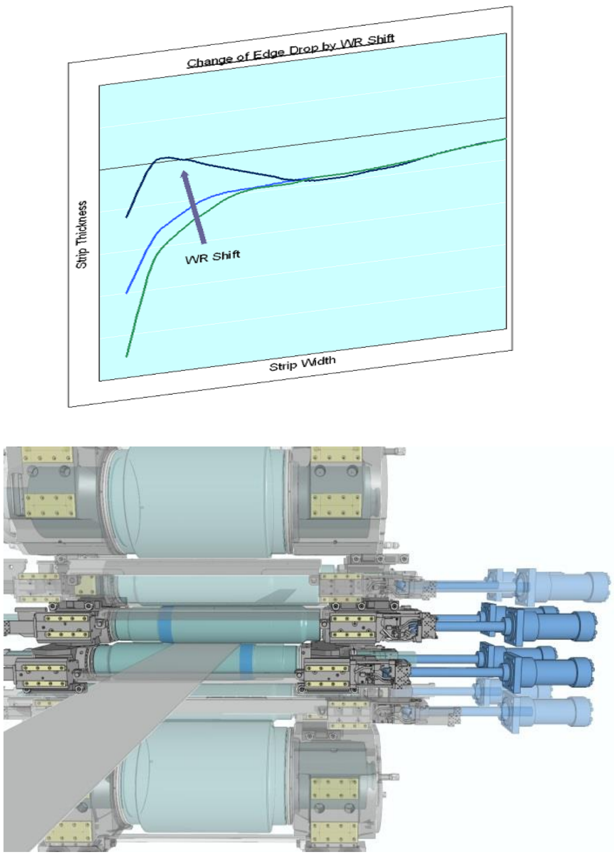


Figure 5. Edge drop control concept.

5. HYPER UCM-MILL

Another attractive solution utilizing the benefits of small diameter work rolls in a tandem cold mill or a reversing cold mill is the 6-high Hyper Universal Crown Control Mill (Hyper UCM-Mill, cf. also [2]) which is a further development of UCM technology.

Although the UCM mill is capable of processing middle grade electrical steel in a 5-stand configuration, the growing demand for thinner and higher silicon content material led to the development of the Hyper UCM-Mill. In order to apply smaller diameter work rolls to a TCM, a comprehensive study of the influence of work roll diameter on the shape control capability, Hertzian Stress between rolls and the reduction ratio was carried out. The study focused on the reduction capacity of the tandem mill. Rolling loads can be reduced and higher reduction ratios can be obtained by using work rolls with smaller diameters. This study showed that the highest reduction ratio is achieved with work rolls having a diameter app. 20-40% smaller than those of the standard UCM mill.

However, if the work roll diameter to maximum strip width ratio is reduced to less than 20% by introduction of smaller diameter work rolls, an intermediate roll drive system is required (Flex-HI, cf. also Figure 7) due to the insufficient strength of the spindle used in a work roll drive system.

Under the above-described limitations, the optimum work roll diameter was found in a range of 230 mm to 290 mm for a Hyper UCM-Mill with a maximum width of app. 1300mm (4 feet).

A new gear-type spindle capable of transmitting higher torque with small diameter work rolls was also developed. This technology called “New MH-Spindle” can transmit 2.7 times the torque of a conventional Universal Joint (UJ)-type spindle.

As a result, the Hyper UCM-Mill was developed as a new rolling mill which uses these smaller work rolls and high strength spindles to enable rolling of high-strength materials compared to a standard UCM-Mill.

Figure 6 shows a comparison of roll arrangements between standard UCM and Hyper UCM-Mill.

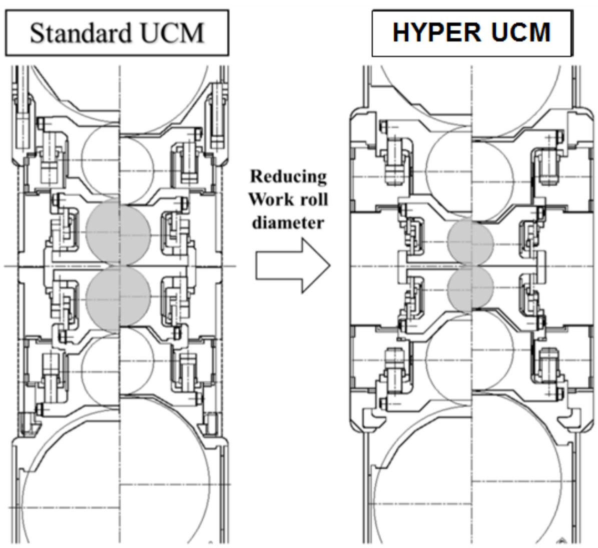


Figure 6. Roll arrangement of standard UCM and HYPER UCM.

Figure 7 shows a historical overview of mill stand technologies with decreasing trend of the ratio of work roll diameter to the maximum strip width. While for a classical 4-high mill, this ratio is typically around 30% and above. A 6-high UCM-Mill shows a ratio of about 25%. The Hyper UCM-Mill utilizes even smaller diameter work rolls and keeps the benefits of the standard UCM mill including work roll drive, and is therefore ideally suited for rolling advanced high-strength steel and high-Si electrical steel. Flex-HI technology with its 18-high mode and a ratio of about 10% offers the capability to produce high-strength steel grades down to a very low gauge, while still keeping the high productivity with low/medium strength steels of a work roll driven 4-high.

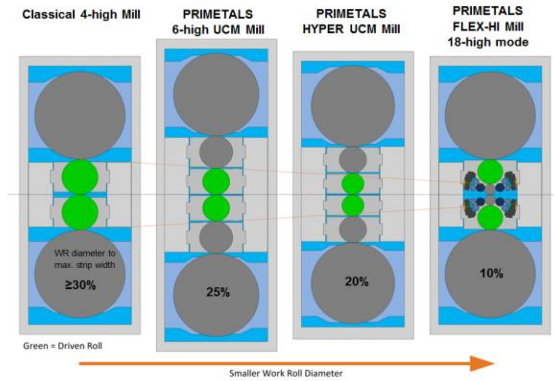


Figure 7. Overview of historical trend to reduce the work roll diameter (green rolls represent driven rolls).

6. ADVANCED 20HI SPLIT HOUSING ZR-MILL: HZ-MILL

As a technology for heavy reduction cold rolling of harder and fragile materials such as grain-oriented or high grade non grain-oriented electrical steel, an advanced 20Hi Split Housing ZR-Mill, called HZ-Mill, was developed by Primetals Technologies as a 20Hi Cluster mill with a split inner housing, replacing the conventional large-scale mono-block type 20Hi ZRM by using very small diameter rolls.

* *Technical contribution to the 11th International Rolling Conference, part of the ABM Week 2019, October 1st-3rd, 2019, São Paulo, SP, Brazil.*

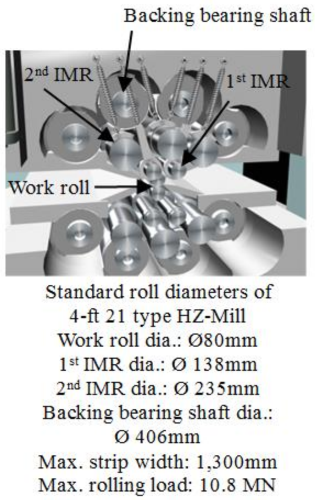


Figure 8. Mill front view and inner housing of HZ-Mill

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 (double AS-U, first intermediate roll shifting and independent leveling function) were incorporated by utilizing the high rigidity and features of this structure.

The HZ-Mill has a 20Hi cluster roll arrangement (cf. Figure 8), in which the ultra-small diameter work rolls (2 rolls, e.g. Ø80 mm) 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 from Primetals Technologies are mounted directly on the OP and DR side push-up cylinders.

7. STRIP HEATING PRIOR TO COLD ROLLING (WARM ROLLING)

Cold rolling of high-silicon electrical steel (Si ≥ 2.5%) is characterized by an increased risk for strip breaks. The main reason is due to the high brittleness of high-Si steels at typical cold rolling temperatures. The high brittleness of the strip material in combination with high rolling loads (strip tension, contact pressure and shear stresses in the roll bite) during cold rolling can lead to generation and grow of edge cracks which can lead to strip breaks and significant production downtimes and delays. It is known that the strip material brittleness can be significantly reduced by increasing the strip temperature before cold rolling (cf. e.g. [1]). The strip temperature at the entry of a tandem mill is typically at room temperature (app. 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 lead to increased room temperature brittleness and consequently reduced toughness and formability during cold rolling.

Figure 9 shows a ductile-to-brittle transition temperature diagram (DBTT), which was determined by a servo-hydraulic high speed testing machine (cf. [1]). The depicted DBTT is for 3.4% Si non-grain oriented (NGO) electrical steel considering different deformation (strain) rates. At typically high deformation rates (cf. curve at 100 s^{-1} in Figure 9) for cold rolling the ductile-to-brittle transition temperature occurs in this case approximately at room temperature (here 22°C). This means that cold rolling at room temperature represents a potential risk for strip breaks because of the reduced fracture elongation and high brittleness of the strip material. Reducing the deformation rate, i.e. reducing the strip speed and/or reduction, or increasing the strip temperature improves the ductility, formability and hence reduces the risk for edge crack propagation and strip breaks significantly.

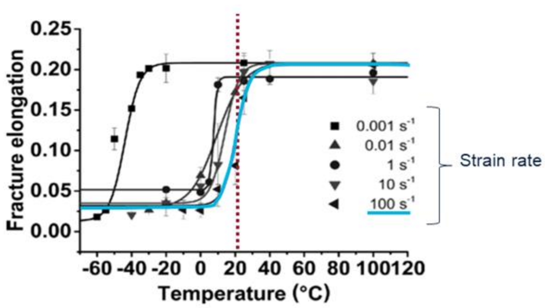


Figure 9. Ductile-to-brittle transition temperature (DBTT) for a 3.4% Si steel (source: [1])

In order to reduce strip break ratio during production of high-grade silicon steels and ultra high-strength steels (UHSS) in tandem mills an induction heating device can be installed in front of the rolling mill. This induction heater allows to raise the strip temperature to e.g. 80°C to 160°C before “Warm Rolling” in the first tandem mill stand. This improves the formability of the strip material and supports a stable rolling operation at high availability of the line. Additionally this allows to increase mill speed or reduction (higher deformation rate) which can lead to higher productivity resp. rolling capability of the cold rolling mill especially for the production of high-silicon electrical steels and UHSS grades.

8. FLEXIBLE LUBRICATION WITH MINIMUM QUANTITY LUBRICATION MQL

Minimum Quantity Lubrication (MQL) is a novel roll-gap lubrication technology for cold-rolling mills (cf. also [3]), applying neat rolling oil atomized with air directly onto the surfaces of the work rolls. This is especially relevant in light of the growing demand for silicon steels for electrical appliances or advanced and ultra high-strength steel grades (AHSS / UHSS) for the automotive applications.

Figure 10 shows that with MQL the entry side emulsion application is completely replaced by neat oil with low flow rates through the top and bottom MQL headers with quick-exchange oil/air mixing nozzles. The generated oil film layer on work roll surface can be precisely controlled and the amount of oil supplied to the roll bite can be adjusted in a flexible and efficient way. Therefore, MQL allows for an intelligent control of the oil film thickness in the roll-gap, depending on the rolling process requirements. Based on actual process and product parameters, the innovative solution allows control over the optimum amount of oil to maximize rolling efficiency and to secure rolling stability (intelligent forward-slip control).

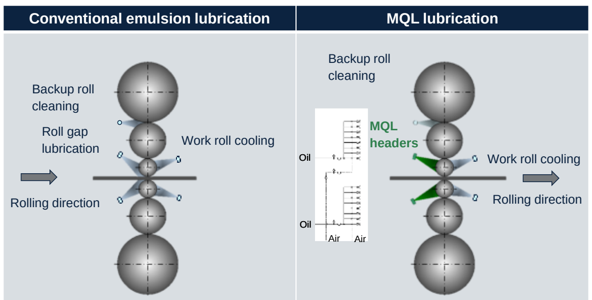


Figure 10. Typical MQL installation, oil/air schematic of spray headers.

MQL not only ensures optimum product-specific lubrication, but the effortless and rapid change of lubrication settings lead to a much higher degree of flexibility than has been previously possible with classical emulsion systems.
After several successful prototype tests, MQL was installed permanently in the batch tandem cold mill of a major European steel producer. It has been in operation for more than two years, delivering outstanding results.
MQL can be installed in one or more mill stands (cf. Figure 10). Each stand is equipped with two spray headers for the top and bottom sides of the strip. These spray bars feature several zones, with only those zones active that are required for a particular strip width. The oil flow, depending on the specific product and pass schedule, is controlled by a process unit that is coupled to the mill automation system through a defined interface. Product-specific lubrication strategies are configured in a preset-table integrated into the existing Level 2 system.

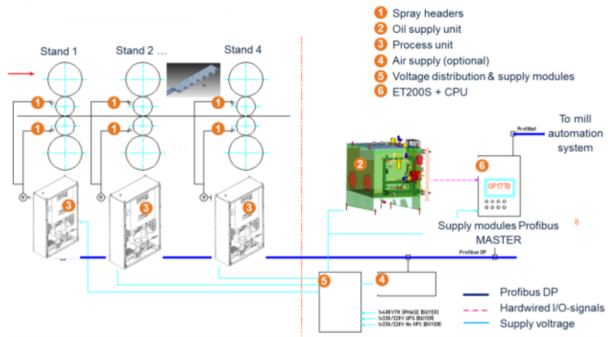


Figure 11. MQL system architecture.

The key to successful production of high-silicon electrical steels and AHSS is to make best use of the capabilities of all available mill stands. This includes making as much reduction as possible in the earlier stands when the material is still relatively soft - at least unless roll flattening issues related to thinner gauges set restrictions in the later stands.
MQL supports the implementation of product-based lubrication by direct control of the oil film thickness on the work roll independent of the rolling speed. Consequently, the friction conditions and therefore the rolling force can be flexibly adjusted even within one coil.
Figure 12 shows an example from the first industrial reference installation were MQL was applied on stand 1 of a TCM. The rolling force level is influenced by the amount of oil applied through MQL. In the first (left) part of the coil, the oil flow rate in ml/min was increased with rolling speed in order to maintain a constant oil application in mg/m². In the second (right) part of the coil, the oil application in mg/m² was increased at constant rolling speed of app. 410 m/min.

In both cases, the rolling force reacts instantly to flow rate and speed changes, and further decreases when the oil application is increased towards the coil tail end. Reduced rolling forces and lower friction levels lead to significant advantages for rolling high-strength materials in the first rolling stands (at low rolling speed and low thickness reduction levels) or during low rolling speeds (e.g. during weld rolling).

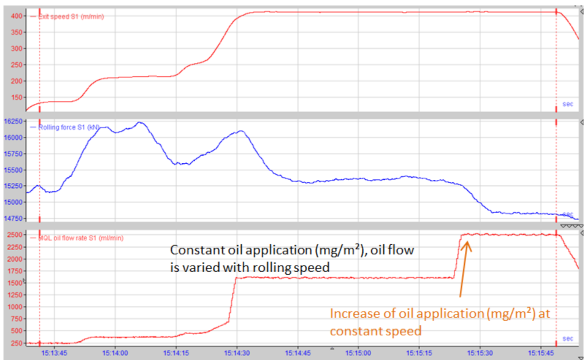


Figure 12. Instant rolling force adjustment by MQL oil application variation within a coil.

Therefore, MQL allows higher reductions on stand 1 for high-strength steels compared to recirculation emulsion lubrication, because the oil film thickness is not limited by the low mill speed and insufficient film formation can be avoided.

9. ACTIVE MILL CHATTER ELIMINATION: CHATTERBLOCK CONTROL

Rolling mills are prone to many different vibration phenomena, especially when rolling high-strength steels in combination with thin product gauges and high mill speed. These mill vibrations can have a significant impact on quality and productivity of the cold rolling process. The most destructive form of mill vibration occurs in a frequency range between 90 Hz and 150 Hz and is called third octave gauge chatter. It is a self-excited vibration, meaning - once initiated - it can grow and quickly diverge leading to instable rolling conditions.

The most prominent drawback of third octave chatter is a severe speed limitation of a more or less large spectrum of production.

A solution that eliminates third octave mill chatter is called ChatterBlock Control® (cf. also [4]) and has been implemented on an industrial cold rolling mill. This first industrial installation was essential for completing the development of this product.

Generally a mill benefits in various ways from the installation of this system, most prominently a significant increase of production capacity.

Main benefits:

- Rolling speed:
  The most obvious advantage is a significant increase of the rolling speed (target: maximum mill speed with chatter critical strips)
- Production:
  Higher production capacity (typical increase of up to 10%)
- Strip breaks, damages in the mill:
  In case of chatter-critical materials, mill operators often try to run the mill close to the limit where third octave chatter occurs (with a permanent danger of a strip break when chatter occurs). The ChatterBlock Control stabilizes the stand, decreases the tendency for vibrations and, therefore, the risk of strip breaks.

- Rolling process:
  Typical production constraints due to a possible chatter occurrence (e.g. lower strip tension to decrease chatter tendency, rerouting of chatter critical strips, more frequent roll changes) are no longer required. The rolling process thus is more stable and more flexible. The overall vibration level is reduced.
- Rolling parameter:
  This also allows a higher flexibility in choosing the rolling parameters (setup values) and allows a better optimization.

Being aware, that this phenomenon is in principle immanent to all tandem cold mills, the target for the product design was a mechatronic system with an interface structure as clear and simple as possible to fit in practically all tandem mills, and certainly to be a modular part of the mill design.
To install the system in any mill, it requires the following modifications (individual adaptations are certainly possible):

- Modification of the existing roll load cylinders for mounting a new valve block
- Attach the system to the existing hydraulic pump system. As an existing hydraulic system typically is designed for a quick roll change (movement of roll load cylinder of several mm/s), the ChatterBlock Control, working only during rolling, should have sufficient energy from the existing hydraulic pump system
- Installation of two acceleration sensors (one on the cylinder housing, one on the piston)
- Installation of two electric cabinets (sensor interfaces, and converter for the directly driven valve) on the stand (two other cabinets in an automation room)
- Interface to the existing automation: the system basically works independently, therefore a minimum interface is required (like an interface to a safety PLC - "emergency off", and a communication to the existing automation system, configurable, minimum on/off switch)

Figure 13 illustrates this concept graphically.

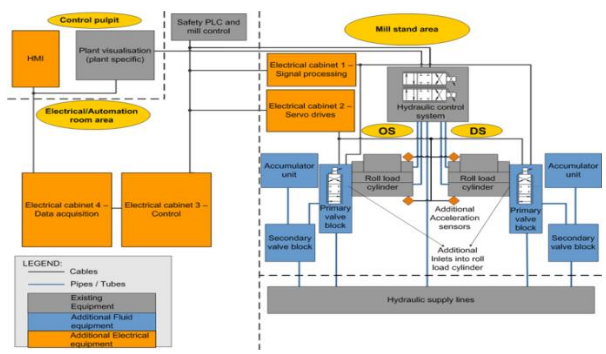
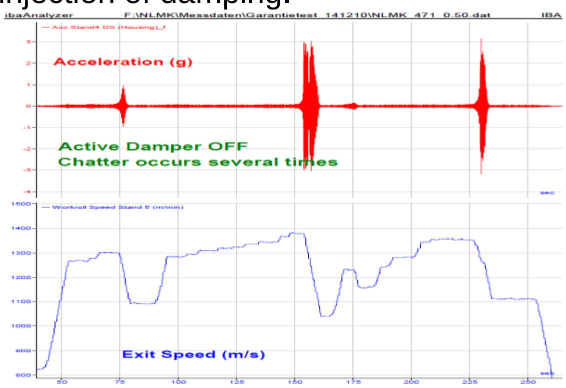


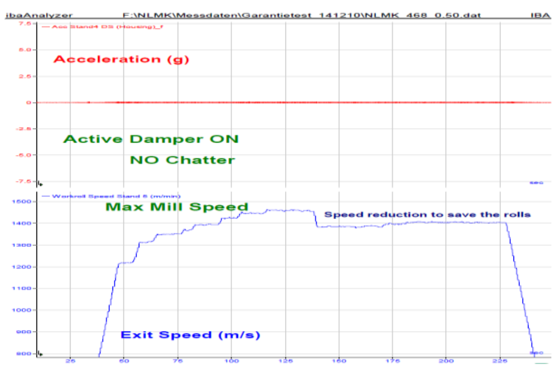
Figure 13. Overall implementation concept of ChatterBlock Control.

The system was tested on an industrial cold rolling mill, as the functionality could only be proven in a real mill where third octave chatter actually occurs.
The idea was to install the new system as a first step on stand 4 of the 5-stand continuous tandem cold mill. This mill was built in the early 1980s and has a significant amount of third octave chatter critical products. Stand 4 is the most chatter-prone mill stand.
Figure 13 shows a typical example of two strips - one with active ChatterBlock Control and one with deactivated system.

With active ChatterBlock Control, the strip could be rolled with maximum mill speed (1450 m/min) without any occurrence of mill chatter. With deactivated ChatterBlock Control, the operator tried several times to increase the speed, but mill chatter occurred each time. This first industrial installation impressively demonstrates the technical functionality of the smart digital solution of stabilizing the mill stand by active injection of damping.



ChatterBlock Control OFF



ChatterBlock Control ON

Figure 14. Comparison of two strips, one rolled with, the other one without ChatterBlock Control.

Based on the results and experiences from the first industrial tests, the system was further developed to include:

- An optimized hydraulic design
- Optimized filter and control algorithms (in cooperation with the University of Linz)
- A new high performance automation system, allowing sample frequencies of the controller of 20kHz!

10. CONCLUSION

This paper describes several innovations to support the successful production of high-grade silicon steels and AHSS / UHSS as well as thinner cold-band gauges.

Classical 4-high cold rolling mills has known technical limitations in terms of reduction capability to roll hard and thin materials, due to its long contact length of roll bite by large work roll diameter and excessive work roll flattening under the high rolling forces involved. This paper shows a historical review of work roll diameter evolution with respect to harder and thinner steels and introduces two new solutions for the production of AHSS / UHSS: Hyper UC Mill and Flex-HI.

Minimum Quantity Lubrication MQL technology overcomes the existing limitations of classical emulsion lubrication technology in terms of flexibility (rapid change of highly different lubrication requirements) and ensures the adjustment of a proper lubrication level with reduced oil consumption. In contrast to state-of-the-art recirculation emulsion systems MQL allows the adjustment of the oil film thickness in the roll-gap independent of the rolling speed. This leads to significant advantages for rolling AHSS / UHSS in the first rolling stands (low thickness reduction levels, high strip surface roughness) or at low rolling speeds (e.g. during weld rolling or flying-gauge cutting).

The trend toward harder and thinner gauges poses more risk for unwanted mill vibrations. To overcome the risk of equipment damage and product quality degradation, ChatterBlock Control eliminates third octave gauge chatter, which supports a high-productivity and high-quality production of AHSS.

REFERENCES

[1]: J. Kwon, H. Huh, and J. Kim, 'Evaluation of the Ductile-to-Brittle Transition Temperature of a Silicon Steel Under Various Strain Rate Conditions With a Servo-Hydraulic High Speed Testing Machine', *Met. Mater. Int.*, vol. 23, no. 4, pp. 736–744, 2017.

[2]: D. Hikino, Y. Nakajima, I. Nakayama, S. Yasunari (2017), Newly developed universal crown control mill "HYPER UCM" for rolling of high-hardness and thinner steel, 3rd European Steel and Technology and Application Days, Vienna, Austria, June 26-29, 2017.

[2]: M. Bergmann, K. Krimpelstaetter (2017), Substituting traditional emulsion lubrication in tandem cold mills, AISTECH 2017, Nashville, USA, May 8-10, 2017.

[3]: G. Keintzel, C. Proell, K. Krimpelstaetter (2016), ChatterBlock Control: Successful elimination of third octave mill chatter in tandem cold rolling, 10th International Rolling Conference and 7th European Rolling Conference, Austria, June 6-9, 2016.