

New insights into the online LUS grain size measurements

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In a collaborative initiative, an innovative laser-ultrasonic (LUS) device was installed at SSAB's Hot Strip Mill (HSM) in Borlänge. This measuring device, along with the software for signal processing and evaluation, was developed, constructed, and implemented through a partnership involving SSAB, Swerim, EMG, and SMS group. Positioned downstream of the last rolling stand in the finishing mill, the austenite grain size is measured immediately after rolling. The LUS measurements were conducted on various steel grades with different dimensions and process parameters. The calculated process data for the tested strips were sourced from the SMS process models (PSC® pass schedule model and CSC cooling section model) and underwent comprehensive analysis alongside the measured process data and austenite grain size. This analysis encompasses the entire process, beginning with the discharge of slabs from the reheating furnaces, through the roughing mill, coil box, finishing mill, and cooling section, and concluding with the downcoiler. Extensive recalculations using the models PSC® and CSC were performed to quantify the correlation between the measured austenite grain size and the process conditions of the rolled strips. The detailed recalculations demonstrate a strong correlation with the measured grain sizes. Based on the results, for example, variations in the transfer bar thickness were carried out, leading to a more equal grain size along the strip length, which has also a noticeable effect on the subsequent cold rolling process.

In the near future, the LUS measurements could be fully integrated into the Level 2 automation system, thus enabling the use of the austenite grain size within the PSC® pass schedule model, the CSC cooling section model, and the MPM microstructure property model. Consequently, these models could utilize the austenite grain size as a setpoint for direct process control in the hot rolling mill, thereby improving control of product properties and minimizing downgrading.

KEYWORDS: LASER ULTRASONIC; HOT ROLLING MILL; MICROSTRUCTURE; PROCESS MODEL; AUSTENITE GRAIN SIZE; MEASURING DEVICE; MICROALLOYED STEEL.

INTRODUCTION

The manufacture of microalloyed high-strength steels is a complex process requiring advanced technologies and the corresponding know-how to attain the desired mechanical properties. These steels often contain small amounts of alloying elements such as niobium, vanadium, titanium, molybdenum, and boron, which have a significant influence on the microstructure of the steel. With this composition, the steels demonstrate an excellent balance of strength, toughness, and weldability. These properties make them particularly suitable for demanding applications in various industries, such as the construction industry for load-bearing structures, the automotive industry for lighter and safer vehicle bodies, and the pipeline industry for transporting oil and gas. A

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remarkable feature of these steels is their high strength, with values ranging from 275 to 750 MPa combined with good formability [1, 2].

In addition to the chemical composition used, the microstructure of a material mainly determines the mechanical and physical properties, including strength, ductility, hardness, resistance to corrosion, and wear. Of particular importance is the austenite grain size, found at high temperatures during hot forming. Smaller austenite grain sizes impede the spread of dislocations, which increases strength, makes crack propagation more difficult, and simultaneously improves ductility. This effect is deliberately exploited, particularly with microalloyed steels.

By adding niobium (Nb) and titanium (Ti), the austenite grain size can be effectively controlled and reduced already during hot rolling. These elements form fine precipitates that inhibit grain growth during heating and rolling (grain-boundary pinning) and result in finer austenite grains. Dissolved niobium accumulates predominantly at austenite grain boundaries and delays their movement (solute-drag effect), thus restricting the growth of the austenite grains [3, 20, 21].

In hot rolling, steel is formed at high temperatures (800-1200°C) and a desired final thickness is attained. This leads to a refinement of the austenite grain, which has a positive effect on the mechanical properties. A precise determination of the microstructural changes occurring in the material and of the austenite grain structure during hot rolling is important not only for achieving the desired dimension but also for the resulting material properties. Innovative, non-contact measurement methods could enable precise process control and significantly increase product quality and efficiency in the hot rolling process.

This is where laser-ultrasonic measuring method comes into play, a non-contact technique that uses lasers to generate and detect ultrasonic waves. The method utilizes pulses from an excitation laser and a second laser to detect the waves, allowing precise analysis of the material properties without physical contact. This technology is particularly suitable for measuring the austenite grain size

and other microstructural variables during hot rolling, as it functions at high temperatures and with moving objects. It has been demonstrated that laser ultrasonic can analyze the grain structure in real time, including the direct measurement of dynamic recrystallization during deformation, which is crucial for process control [4, 18, 19].

The data obtained with laser ultrasonics can be directly processed in process models, which are used in hot strip production for plant control during rolling and cooling. The setup model (PSC®, Pass Schedule Calculation) calculates the load distribution during forming and defines the pass schedule to achieve the desired strip thickness. Key aspects here are the ductility of the material and the rolling temperature, which are important for the recrystallization behavior of the material during forming. The cooling model (CSC, Cooling Section Control) determines the volume of water required to attain a specific temperature distribution in the cooling section. Here, the exact description of the transformation process and the energy balance play a significant role in solving the transient heat conduction equation, as the austenite grain size influences the transformation behavior [5].

This work describes the evaluation of process data for the roughing and finishing mills collected during hot rolling at SSAB's HSM in Borlänge and the comparison between simulated and measured austenite grain sizes. It demonstrates how the austenite grain size develops along the strip length under various process parameters [6]. In addition, the influence of the measured austenite grain size on the required water quantities in the cooling section is examined.

METHODOLOGY AND PARAMETERS

Figure 1 shows the HSM at SSAB in Borlänge viewed from left to right, starting with the reheating furnaces, the roughing mill, the coil box, the finishing mill, the cooling section, and the downcoilers.

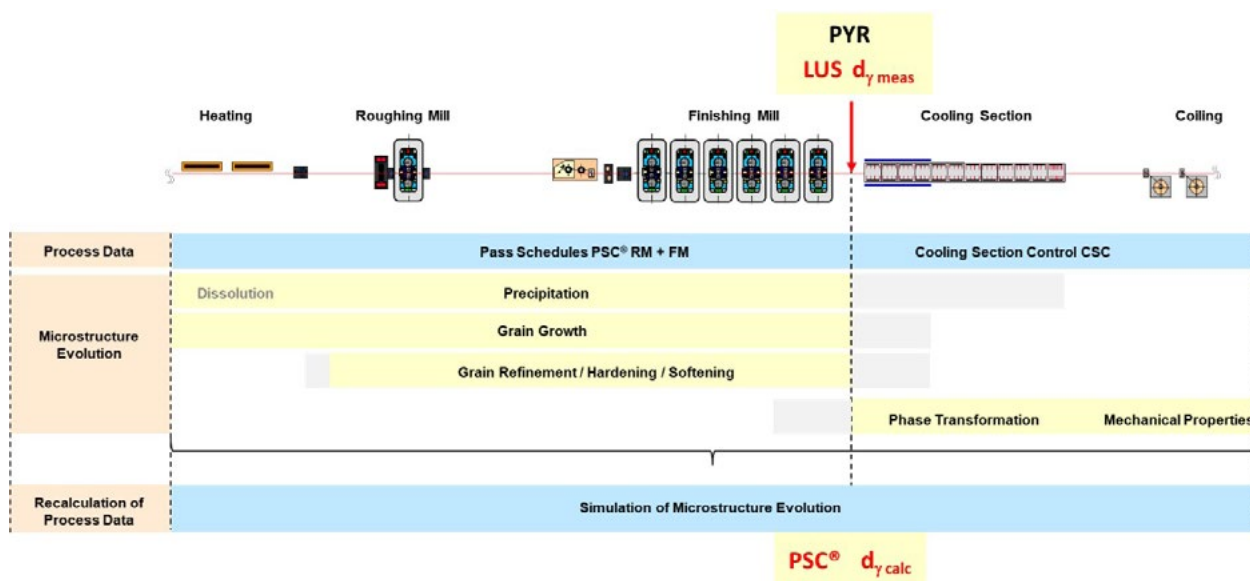


Fig.1 - HSM SSAB, Borlänge - Process data - Simulation of the microstructure evolution.

The newly installed LUS measuring device, shown in figure 2, is located in the HSM below the finishing mill pyrometer (see figure 1).

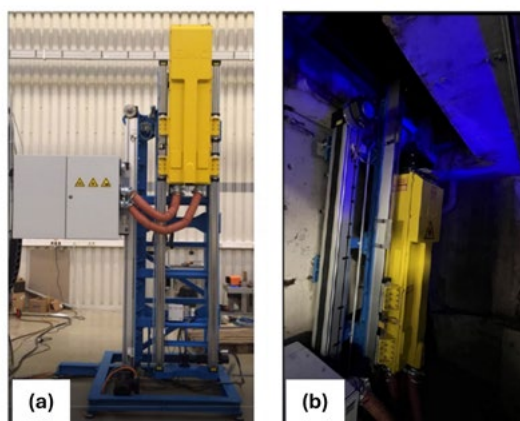


Fig.2 - LUS measuring device: (a) during the test phase at EMG's workshop in Wenden, showing the power supply (gray) and the laser unit (yellow); (b) installed at SSAB's HSM in Borlänge, positioned on vertical rails with a working distance of 60 cm from the rolled strip.

Figure 2(a) shows the new LUS measuring device during the test phase at EMG's workshop in Wenden. Shown are the power supply (gray) and the optical head with the lasers (yellow). The measuring device can be moved vertically along the visible rails, as shown in figure 2(b). During rolling, it is moved into position beneath the rolled strip with a working distance of 60 cm.

Grain size determination by laser ultrasonics follows four sequential steps, as described in detail by Malmström et

al. [4, 18]: (a) generation of broadband ultrasound by laser ablation, (b) detection of the surface response for multiple backwall echoes, (c) calculation of the frequency-dependent attenuation, and (d) conversion to grain size via a calibration curve. These steps are illustrated schematically in figure 3.

The total ultrasonic attenuation, α , can be decomposed into three contributions [4]:

$$\alpha = \alpha_{\text{abs}} + \alpha_{\text{diff}} + \alpha_{\text{scat}}$$

where α_{abs} represents material absorption, α_{diff} is the frequency-dependent grain scattering. The scattering contribution follows:

$$\alpha_{scat} \sim K(T) \cdot D^{n-1} \cdot f^n$$

where n depends on the scattering regime (Rayleigh: $n = 4$; stochastic: $n = 2$), D is the mean grain diameter, f is the frequency, T is the temperature, and $K(T)$ accounts for temperature-dependent elastic anisotropy. In the frequency range of approximately 1-40 MHz relevant here, setting $n = 3$ provides a practical linearization [4], reducing the total attenuation to:

$$\alpha = a + b \cdot f^3$$

where a is a constant offset comprising material absorption and other non-scattering contributions, and:

$$b = K(T) \cdot D^2$$

Since only the third-order attenuation coefficient, b , contains information of grain size, the mean grain diameter is obtained as [4]:

$$D = \Gamma(T) \cdot \sqrt{1000 \cdot b}$$

where $\Gamma(T) = 1/\sqrt{K(T)}$ is a temperature- and material-dependent transfer function. In practice, this calibration function is determined experimentally by comparing LUS

attenuation measurements on reference samples with grain sizes obtained by optical microscopy or by EBSD with parent-grain reconstruction [4].

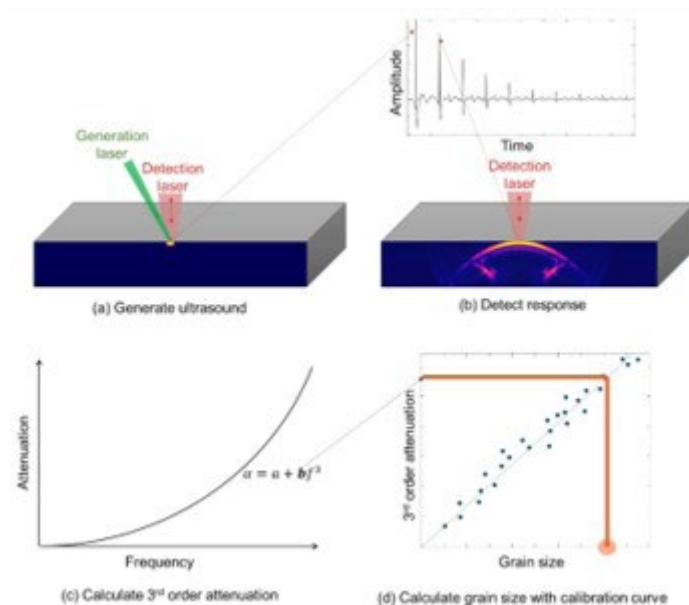


Fig.3 - Steps in LUS grain size determination: (a) generation of broadband ultrasound by laser ablation, (b) detection of the surface response from multiple backwall echoes, (c) calculation of the frequency-dependent attenuation, $\alpha = a + b \cdot f^3$, and (d) conversion to grain size via calibration curve. Adapted from Malmström et al. [4].

The L2 online setup models of the roughing and finishing mills each calculate the pass schedules and transmit them to the L1 control systems, with defined interfaces facilitating communication between the models themselves

(see also figure 1 - Process Data). The same applies to the L2 online setup model of the CSC cooling section, which calculates the required water quantities in the individual zones of the cooling section based on the input variables

and also transmits these to the L1.

The online process data from the PSC® RM and FM setup models were recalculated using the model PSC® Offline in order to generate a closed representation of the operating mode. Based on the closed time-temperature-deformation history, it is possible to simulate the microstructure evolution from the furnace exit to the finishing mill pyrometer, where the measured grain size can then be compared with the simulated austenite grain after the last hot-rolling deformation.

The simulation of microstructure evolution starts from a standard austenite grain size at the slab extraction temperature upon exit from the reheating furnace. It is assumed that all microalloying constituents, such as niobium, are fully dissolved. During transport to the roughing stand, potential grain growth and the temperature evolution are calculated. Furthermore, grain refinement (i.e., recrystallization during forming in the roughing and finishing mills) and possible grain growth after full recrystallization are taken into account [7-9].

If the slab contains microalloying elements, such as niobium, the precipitation behavior is simulated as a function of temperature, recrystallization kinetics, and deformation. The niobium content remaining in solution at the end of the finishing mill, for example in the penultimate stand, is included in the calculation of the critical degree of deformation and other model variables.

Governing Equations for Microstructure Evolution

The simulation of microstructure evolution within the PSC® pass schedule model follows well-established physically based formulations for recrystallization kinetics, grain growth, and precipitation. The core equations are briefly summarized below.

Recrystallization Kinetics (JMAK)

The fraction recrystallized, X_r , as a function of time, t , is described by the Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation [11, 12]:

$$X_r(t) = 1 - \exp\left(-\ln 2 \cdot \left(\frac{t}{t_{0.5r}}\right)^n\right)$$

where $t_{0.5r}$ is the time for 50% recrystallization and n is the Avrami exponent, which depends on the nucleation and growth mechanism. The parameter $t_{0.5}$ is commonly ex-

pressed as a function of the initial grain size D_0 , the strain ε , the strain rate $\dot{\varepsilon}$, and the temperature T [13, 20]:

$$t_{0.5r} = A \cdot \varepsilon^{-p} \cdot \dot{\varepsilon}^{-q} \cdot D_0^s \cdot \exp\left(\frac{Q_{rex}}{RT}\right)$$

where A , p , q , and s are empirically determined material constants, Q_{rex} is the activation energy for recrystallization, and R is the universal gas constant.

Grain Growth

Following complete recrystallization, grain growth is governed by a modified grain-growth law that accounts for the retarding influence of second-phase particles present in the microstructure [14, 20]:

$$D^m - D_0^m = B \cdot \exp\left(-\frac{Q_{gg}}{RT}\right) \cdot t$$

where D is the grain diameter at time t , m is the grain-growth exponent, B is a material-dependent pre-exponential constant, and Q_{gg} is the activation energy for grain boundary migration. When finely dispersed particles are

present—such as those formed by microalloying elements—grain boundary migration is impeded by a Zener drag pressure, P_Z [14, 15]:

$$P_Z = \frac{3F_v\gamma}{2r}$$

where F_v is the volume fraction of particles, γ is the grain boundary energy per unit area, and r is the mean particle

radius. Grain growth effectively ceases when the driving pressure for growth falls below P_z , yielding a limiting grain size, D_{lim} :

$$D_{lim} = \frac{4r}{3F_v}$$

Precipitation Kinetics – Nucleation and Growth of Second-Phase Particles

In microalloyed steels, the precipitation of carbides, nitrides, and carbonitrides of elements such as niobium,

titanium, or vanadium plays a central role in controlling austenite grain size and recrystallization behavior. The nucleation rate $\dot{N}$ of precipitate particles is described by classical nucleation theory (CNT) [16, 17]:

$$\dot{N} = N_0 \cdot \exp\left(-\frac{\Delta G^*}{k_B T}\right) \cdot \exp\left(-\frac{Q_{diff}}{RT}\right)$$

where N_0 is the pre-exponential factor, k_B is the Boltzmann constant, Q_{diff} is the activation energy for solute

diffusion, and ΔG^* is the critical Gibbs free-energy barrier for nucleation:

$$\Delta G^* = \frac{16\pi\sigma^3}{3(\Delta G_V)^2}$$

Here, σ is the precipitate-matrix interfacial energy, and ΔG_V is the volumetric driving force for precipitation,

which is a function of the degree of supersaturation S of the relevant solute elements in the austenite matrix:

$$\Delta G_V = -\frac{RT}{V_m} \ln S$$

where V_m is the molar volume of the precipitate phase. The supersaturation S is defined as the ratio of the actual

ionic activity product of the dissolved alloying elements to the temperature-dependent solubility product $K_{sp}(T)$ of the respective precipitate [17]:

$$S = \frac{\prod_i [M_i]^{v_i}}{K_{sp}(T)}$$

where $[M_i]$ denotes the concentration of solute species i and v_i is the corresponding stoichiometric coefficient, making this formulation applicable to a wide range of precipitate chemistries.

The overall precipitation kinetics—encompassing nu-

cleation, growth, and coarsening—are frequently represented in an analogous JMAK framework. For the case of strain-induced precipitation, as described by Dutta, Palmiere, and Sellars [9], and further corroborated for Nb-V multi-component systems [21]:

$$X_p(t) = 1 - \exp\left(-0.693 \cdot \left(\frac{t}{t_{0.05}^p}\right)^{n_p}\right)$$

where X_p is the precipitated fraction, $t_{0.05}^p$ is the time for 5% precipitation, and n_p is the precipitation Avrami exponent.

LUS measurements were conducted in the hot strip mill

during rolling for 287 strips with the following parameters (table 1), consistent with online measurement approaches reported for comparable industrial hot strip mill installations [19]:

Tab.1 - Process parameters and chemical composition ranges of the 287 strips investigated.

Furnace temperature:	1180 - 1290 °C	C content:	< 0.39 wt.-%
Final rolling temperature:	820 - 920 °C	Mn content:	< 2.3 wt.-%
Slab thickness:	217 - 223 mm	Nb content:	< 0.045 wt.-%
Transfer bar thickness:	26 - 31 mm	Ti content:	< 0.1 wt.-%
Final thickness:	2 - 12 mm	N content:	< 0.007 wt.-%
Strip width:	815 - 1600 mm		

RESULTS

Using the example of strip A, figure 4 shows the results of the recalculation of the operation, i.e., the rolling forces in roughing (a) and finishing mill (d)-(i), temperatures (c) and (k), and speeds (b) and (j) and the comparison of the measured and recalculated austenite grain size (l). In principle, the LUS device can measure from the first centimeter of

the strip; here, however, due to conservative safety margins, the LUS measurement starts after the strip head end has passed the measuring point and ends before reaching the strip tail end. Hence, some LUS data are missing at both ends of the strip. The available measured values are synchronized over the strip length.

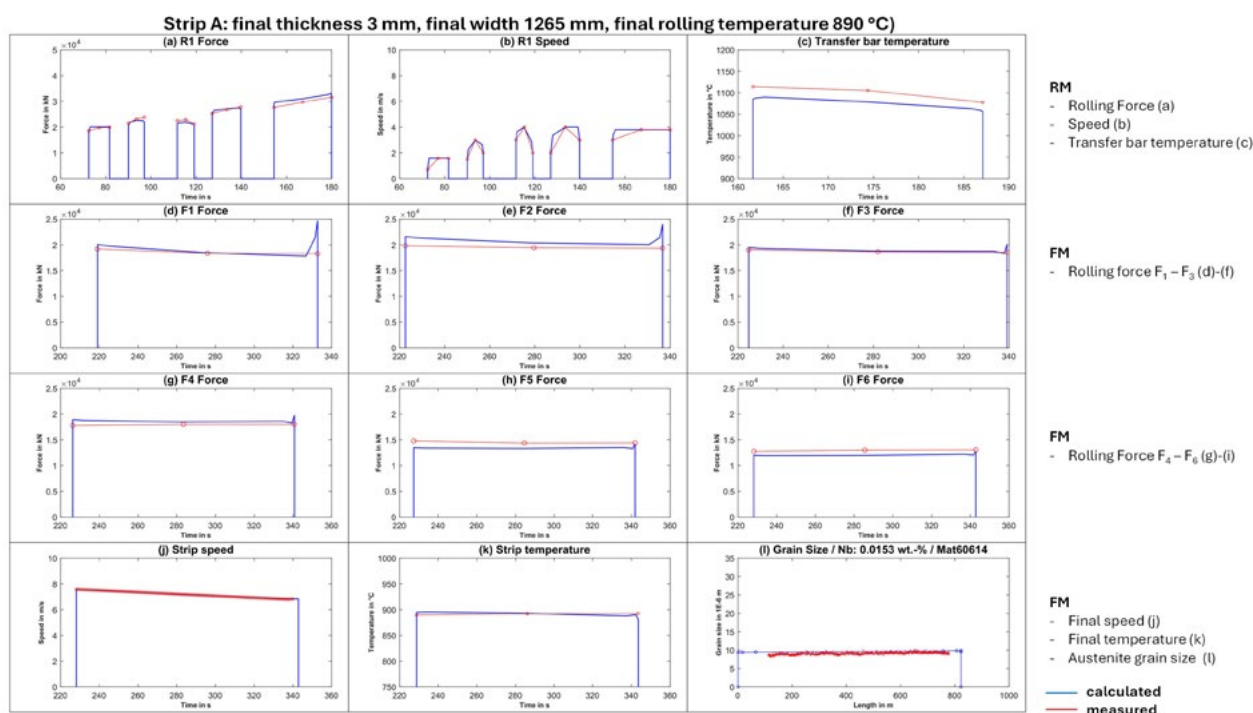


Fig.4 - Recalculation of pass schedule items for strip A: rolling forces in roughing (a) and finishing mill (d)-(i), temperatures (c) and (k), and speeds (b) and (j), including a comparison of the measured and recalculated austenite grain size (l) (red - measurement results; blue - calculation results of model PSC® Offline).

In general, there is a very good match between the measured rolling forces, rolling speeds, and temperatures. Only the recalculated transfer bar temperature (c) is approximately 15-20°C below the measurement. The re-

calculated strip speed (j) at the finishing mill pyrometer is in good agreement with the measured values, which is reflected in the precise time mapping of the online pass schedules within the model PSC® Offline system. The

finishing strip temperature (k) shows small deviations between the calculation and measurement. Of particular note is the good match between the measured and recalculated austenite grain size (l), which stands at on the order of 10 μm . This means that PSC® Offline, based on the recalculated pass schedules, is well suited to simulate the metallurgical processes of grain growth, recrystallization, and precipitate formation, thereby enabling accurate reproduction of the measured LUS austenite grain size.

Figure 5 shows comparisons of the measured and recalcu-

lated austenite grain size for 12 strips (B - M), which again demonstrate a very good match. Strips B and C each show a small gradient both in the measurement and in the recalculation, with the recalculated austenite grains approximately 1-2 μm larger than the measured grains. In the case of strip D, the calculated austenite grain size is approximately 15 μm and the measured size around 12 μm . The reason for this discrepancy has not yet been definitively determined.

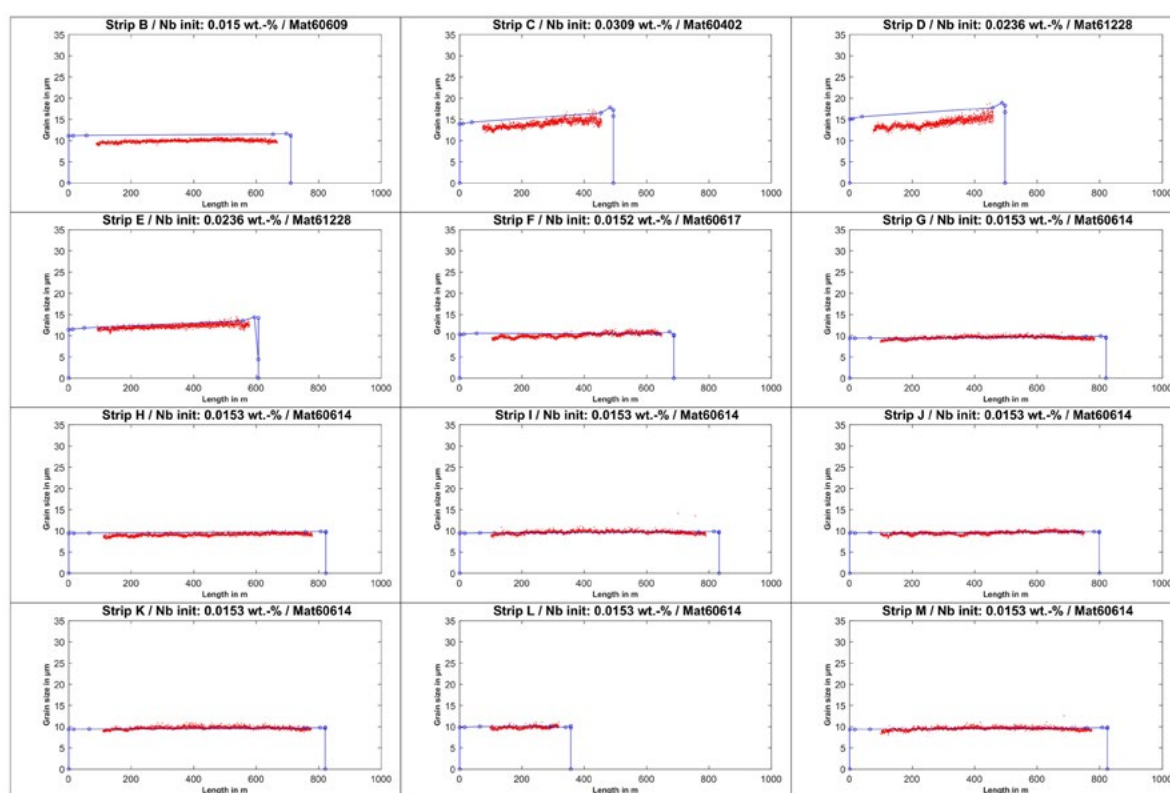


Fig.5 - Comparison of the measured and recalculated austenite grain size of 12 strips: (a) Strip B, (b) Strip C, (c) Strip D, (d) Strip E, (e) Strip F, (f) Strip G, (g) Strip H, (h) Strip I, (i) Strip J, (j) Strip K, (k) Strip L, (l) Strip M. (red - measurement results; blue - calculation results of model PSC® Offline).

Figure 6 shows comparisons of the measured and recalculated austenite grain size for 7 strips (N - T), which again demonstrate a very good match. A conspicuous feature of figure 6 is strip Q with its pronounced waveform. The pronounced waveform, with an amplitude of approximately 3 μm , may be due to cold spots as the material exits the

furnace. It has not yet been definitively clarified whether this represents an inhomogeneity in the austenite grain size upon exiting the furnace or whether the phenomenon may be attributable to the differences in the dissolved state of Nb.

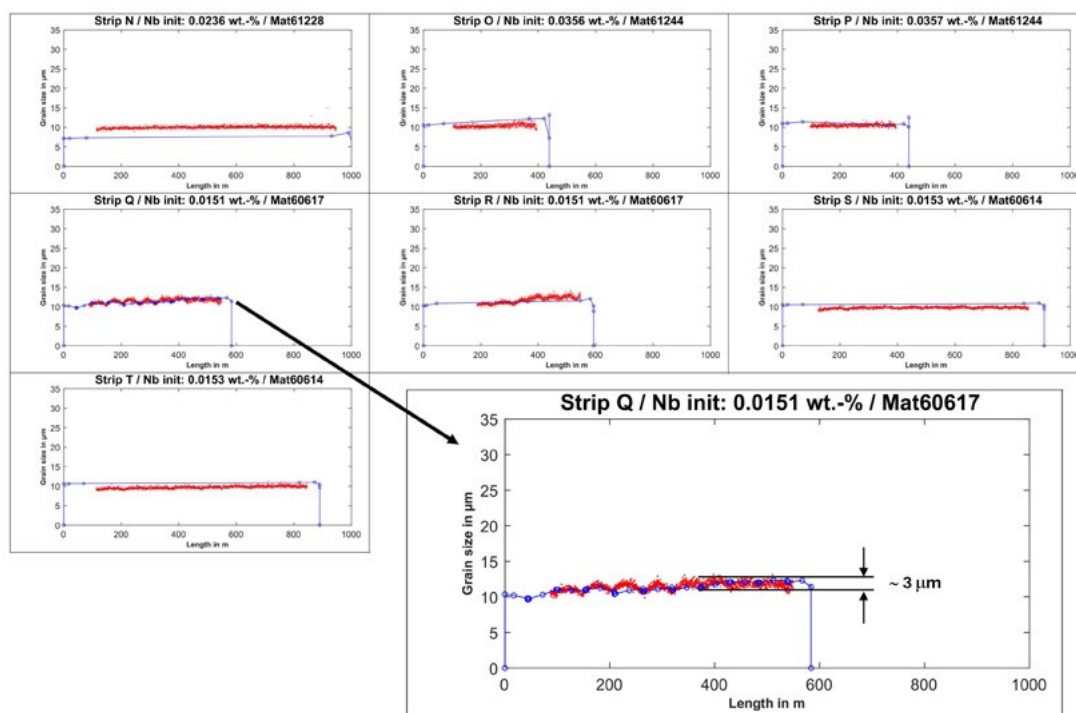


Fig.6 - Comparison of the measured and recalculated austenite grain size of 7 strips: (a) Strip N, (b) Strip O, (c) Strip P, (d) Strip Q, (e) Strip R, (f) Strip S, (g) Strip T. (red - measurement results; blue - calculation results of model PSC® Offline).

The waveform of strip Q can also be seen in the recalculation of the austenite grain size. Here, the sensitivity of the LUS measuring device is particularly evident, as is the capability of the model PSC® Offline to reproduce this behavior. Based on the recalculations shown, further optimization calculations were performed to standardize the austenite grain size during rolling. Figure 7(a) shows the progression of the measured and recalculated austenite grain size of strip U, which serves as reference. At a transfer bar thick-

ness of 26 mm, the measured values show a slight curvature in the first half of the strip followed by an increase from 13 to approximately 17 µm. During optimization, the transfer bar thickness has proven to be a potential influencing parameter on the recrystallization behavior and, consequently, the austenite grain size; therefore, it was adjusted in small increments, i.e., increased, during the rolling program.

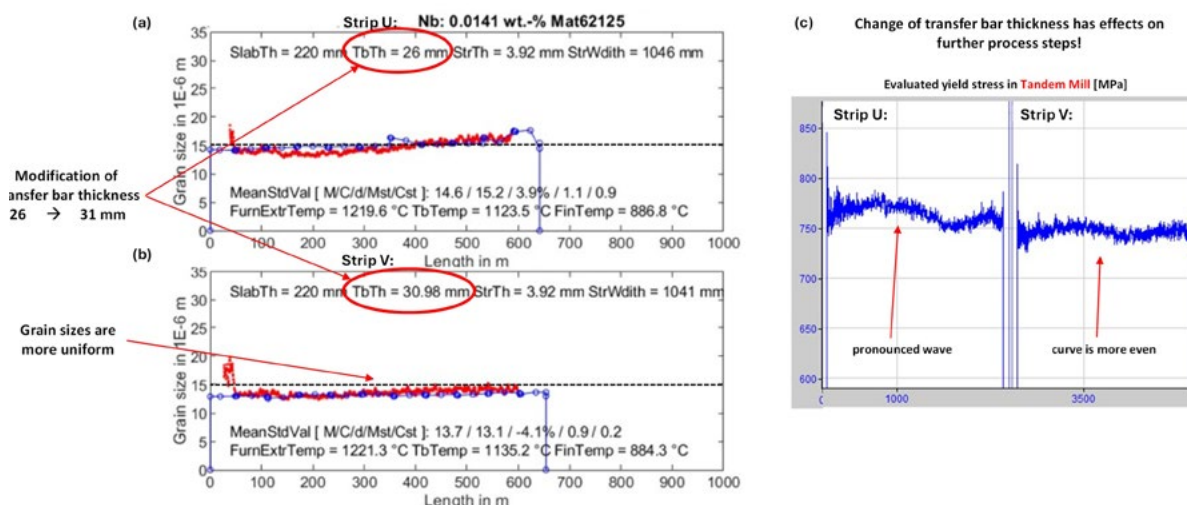


Fig.7 - Increase in the transfer bar thickness: (a) measured and recalculated austenite grain size of strip U (transfer bar thickness: 26 mm); (b) measured and recalculated austenite grain size of strip V (transfer bar thickness: 31 mm); (c) strip strength during subsequent cold rolling - comparison of strips U and V.

Figure 7(b) shows the result of increasing the transfer bar thickness from 26 to 31 mm for strip V, i.e., the progression of the measured and recalculated austenite grain sizes. In both the calculation and the measurement, the austenite grain size remains at an almost constant level of approximately 14 μm ; in other words, its progression is clearly more uniform compared with strip U. From a metallurgical point of view, this somewhat smaller and more uniform austenite grain size originates from the higher overall degree of deformation in the finishing mill resulting from the greater transfer bar thickness. This even curve is also apparent in downstream processes in the tandem cold mill, as reflected by the more consistent strength (figure 7(c)). Strip U shows a distinct waveform with scatter in the cold yield point, i.e., a strength of approximately 750–780 MPa, which is not the case for strip V; here, the strength level remains almost constant at around 750 MPa.

The austenitization conditions, particularly the austenitization temperature, the holding time, and the deformation above the transformation temperatures, have a considerable influence on the transformation temperatures and the resulting microstructure of steel grades. This influence can

be attributed above all to the grain size of the austenite. A higher austenitization temperature and/or longer holding time generally lead to a coarser austenite grain size. If the carbides are not completely dissolved, a low austenitization temperature or a holding time that is too short will lead to insufficient homogenization of the austenite. Particular attention should be paid when adding Nb and Ti, as the stable carbides and carbonitrides are difficult to dissolve and at the same time constitute effective grain-growth inhibitors for the austenite. This results in a finer austenite grain during forming [10]. The CSC cooling-section setup model considers the austenitization conditions (PA) as an input variable for calculating the transformation temperatures. Figure 8 shows the influence of grain size—the grain size previously used in the model (upper section of the figure) and the currently measured grain size (lower section)—on the calculated water quantity for three strip thicknesses. In the model, a grain size of approximately 33 μm has been used until now, while the current measured grain size is approximately 13 μm . This difference affects the calculated water quantity.

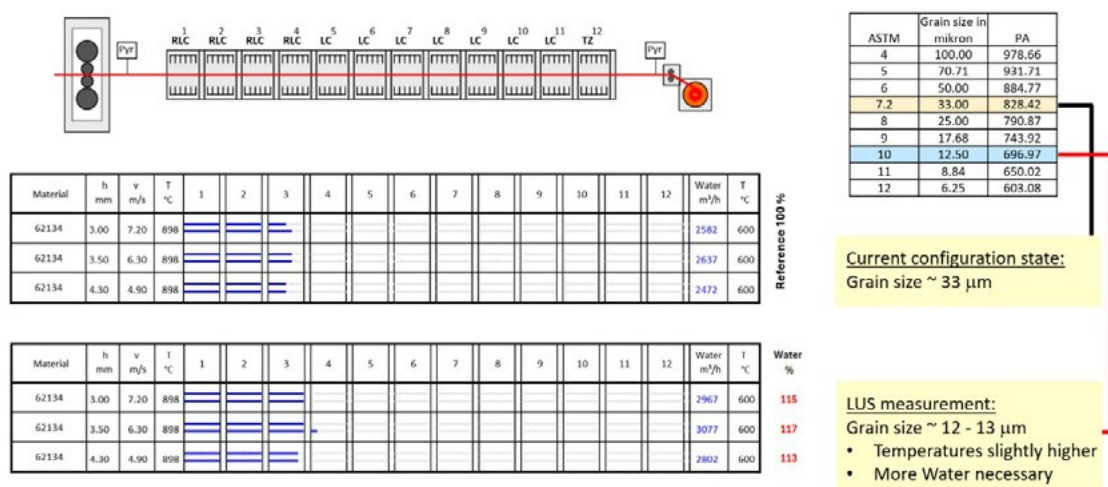


Fig.8 - Recalculated water quantities in the cooling section.

Compared with the reference water quantity (100%, initial grain size: 33 μm), 13-15% more water is required when the recalculation is performed with the measured austenite grain size. From a metallurgical point of view, smaller austenite grains lead to a larger grain-boundary surface area, which in turn forms preferential nucleation sites for ferrite and causes ferrite to form at an earlier stage during cooling. The increased number of nucleation sites accelerates the phase transformation from austenite to ferrite; therefore,

more water is required. For other materials, however, it has been found that there are no, or negligible, changes in the required water quantity when the measured austenite grain size is included as an input variable in the CSC cooling-section model.

CONCLUSION

The newly developed LUS grain-size measuring device was installed and successfully tested in the hot strip mill at

SSAB, Borlänge. For nearly 290 strips covering a wide field of chemical composition and geometrical parameters, the austenite grain size was measured directly during rolling under normal process conditions. Recalculations of the pass schedules using the process model PSC® Offline showed a very good match with both the measured rolling forces and temperatures and the recalculated and measured austenite grain sizes, i.e., with the simulation of grain growth, recrystallization, and precipitation. For some strips, the measurements showed slight gradients that could also be reproduced in the recalculation of the austenite grain size; however, the causes of the observed deviations require further investigation. Of particular note is the pronounced waveform of the measured austenite grain size on some strips, which is likely attributable to cold spots as the material exits the furnace. This high sensitivity of the LUS measuring device is also reflected in the process model PSC® Offline through the recalculation of the austenite grain size.

To achieve improved uniformity of the austenite grain size, an increase in the intermediate strip thickness was derived from optimization calculations and successfully verified during rolling tests. Moreover, the more uniform austenite grain size had positive effects on subsequent process steps; for example, the strength of the tandem cold mill was more consistent. Recalculations of the required water quantities using the CSC cooling-section model and the measured austenite grain size as input showed that some grades required more water due to smaller austenite grains. Going forward, the recalculations of the pass schedules and the simulation of the microstructure evolution will be further optimized and validated by LUS measurements, building on recent advances in the real-time measurement of dynamic recrystallisation by laser ultrasonics. Further rolling trials and series of measurement campaigns with optimized rolling conditions are planned.

Nomenclature

Abbreviations

Abbr.	Definition	Abbr.	Definition
CNT	Classical Nucleation Theory	LUS	Laser Ultrasonic
CSC	Cooling Section Control	MPM	Microstructure Property Model
EBSD	Electron Backscatter Diffraction	PSC®	Pass Schedule Calculation
FM	Finishing Mill	RM	Roughing Mill
GLUS	Gleeble and Laser-Ultrasonics	L1	Level-1 automation system
HSM	Hot Strip Mill	L2	Level-2 automation system
JMAK	Johnson-Mehl-Avrami-Kolmogorov		

Latin Symbols

Symbol	Definition	Unit
A	Pre-exponential factor (Arrhenius-type kinetics, general)	model-dependent
A_0	Pre-exponential factor for nucleation rate	$\text{m}^{-3} \text{s}^{-1}$
a	Empirical material constant (recrystallization / growth model)	—
b	Empirical material constant (recrystallization / growth model)	—
B	Empirical material constant (grain growth / recrystallization kinetics)	model-dependent
c_i	Concentration of solute species i	wt.-%
D	Mean austenite grain diameter	μm
D_0	Initial austenite grain diameter	μm
D_{lim}	Limiting grain size due to Zener pinning	μm
f	Ultrasonic frequency	MHz
F_v	Volume fraction of precipitate particles	—
G	Pre-exponential constant for grain growth	model-dependent
J	Nucleation rate of precipitates	$\text{m}^{-3} \text{s}^{-1}$
k_B	Boltzmann constant	J K^{-1}

K	Temperature-dependent elastic anisotropy factor	model-dependent
K_p	Solubility product	—
K_{sp}	Zener-pinning constant / particle pinning coefficient	model-dependent
m	Grain-growth exponent	—
M	Grain-boundary mobility	$\text{m}^4 \text{J}^{-1} \text{s}^{-1}$
N_0	Initial number density	m^{-3}
$\dot{N}$	Nucleation rate (time derivative of N)	$\text{m}^{-3} \text{s}^{-1}$
n	Avrami exponent for recrystallization	—
n_p	Avrami exponent for precipitation	—
q	Frequency-dependence exponent (ultrasonic attenuation)	—
r	Mean precipitate particle radius	μm
R	Universal gas constant	$\text{J mol}^{-1} \text{K}^{-1}$
S	Supersaturation ratio	—
t	Time	s
$t_{0.5r}$	Time for 50 % recrystallization	s
$t_{0.05p}$	Time for 5 % precipitation	s
T	Temperature	K / °C
ν_i	Stoichiometric coefficient of solute species i in the respective precipitate phase	—
V_m	Molar volume of precipitate phase	$\text{m}^3 \text{mol}^{-1}$
X_r	Recrystallized fraction	—
X_p	Precipitated fraction	—

Greek Symbols

Symbol	Definition	Unit
α	Model constant (ultrasonic scattering / kinetic relation)	—
γ	Grain-boundary or interfacial energy	J m^{-2}
γ_{gb}	Grain-boundary energy per unit area	J m^{-2}
γ_{int}	Precipitate-matrix interfacial energy	J m^{-2}
$\Gamma(T)$	LUS calibration transfer function	model-dependent
ε	True strain	—
$\dot{\varepsilon}$	Strain rate	s^{-1}
σ	Precipitate-matrix interfacial energy	Pa
ΔG^*	Critical Gibbs free-energy barrier for nucleation	J
ΔG_v	Volumetric driving force for precipitation	J m^{-3}
Q_{diff}	Activation energy for solute diffusion	J mol^{-1}
Q_{rex}	Activation energy for recrystallization	J mol^{-1}
Q_{grain}	Activation energy for grain-boundary migration	J mol^{-1}
Q_{gg}	Activation energy for grain growth	J mol^{-1}

Laser-Ultrasonic Attenuation Terms

Symbol	Definition	Unit
α_{tot}	Total ultrasonic attenuation	dB m^{-1}
α_{abs}	Material absorption attenuation	dB m^{-1}
α_{diff}	Diffraction-related attenuation	dB m^{-1}
α_{sc}	Grain-scattering attenuation	dB m^{-1}
β_3	Third-order grain-scattering coefficient	$\text{dB m}^{-1} \text{MHz}^{-3}$
p_Z	Zener drag pressure	J m^{-3}

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