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Real-time work hardening evaluation for optimizing hot rolling schedules and power demand in HSLA steel production

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The proposed paper deal with a novel approach to evaluate the work hardening in the roll bite using the Orowan hot rolling equilibrium equation, under the assumption of a known rolling pressure distribution along the contact arc and the plane strain plasticity condition. This formulation leads to a first-order differential equation, $\frac{d\sigma}{d\varepsilon} = \Omega\sigma$, wherein work hardening is directly proportional to equivalent stress (related to dislocation density and underlying metallurgical complexity) and a function Ω, depending only on strain through the rolling pass geometry. The implementation of this approach in the incremental plasticity framework with iterative calculation scheme, makes it possible to reconstruct the stress-strain path of the material along the deformation history and to identify metallurgical transitions during hot rolling from deviations in the stress–strain response or changes in the work-hardening rate. The off-line predictive module is based on a machine-learning model trained on a large database comprising the results of the real-time module together with additional information on chemical composition, microstructural features, and tensile properties of the final products. A key advantage of the proposed incremental plasticity approach is its ability to drastically reduce the number of required constitutive parameters, thereby improving robustness, transferability, and suitability for real-time industrial implementation.

KEYWORDS: SMART ROLLING, WORK HARDENING, INCREMENTAL PLASTICITY, PLASTIC STABILITY, MACHINE LEARNING, TMCP;

INTRODUCTION

The proposed framework is based on a first-order differential equation, $d\sigma/d\varepsilon=\Omega\sigma$, where the work hardening rate is proportional to the equivalent stress, that, thanks to Taylor equation, is implicitly accounting for the dislocation density and underlying metallurgical state of the material. The function Ω is independent of stress and depends on strain through the rolling pass geometry, reflecting process-related rather than constitutive complexity. The range of validity of this assumption primarily corresponds to deformation regimes in which dislocation accumulation and annihilation dominate the mechanical response, as is typically the case during hot rolling under industrial strain rates. Nevertheless, the proposed methodology is not limited to the study of dislocation hardening: all relevant metallurgical phenomena such as dynamic recovery, recrystallization, or precipitation affect the evolution of the dislocation density and are therefore indirectly captured through changes in the hardening response. As a result, the framework has a broad range of applicability and enables the detection of multiple metallurgical mechanisms via their impact on

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the evolving dislocation state, while maintaining the simplicity required for real-time process control. To develop a robust incremental plasticity model for hot rolling, it is essential to evaluate in real time the material's work hardening behaviour. In hot rolling, the instantaneous flow stress of the steel depends on its temperature and on the accumulated, or residual, strain from each rolling pass. By tracking how the flow stress evolves with successive deformations through a work-hardening law we can accurately reconstruct the stress-strain path in real time. This capability represents the cornerstone of an incremental plasticity framework: it allows the model to update the current material state after each pass, predict subsequent hardening or softening events, and, ultimately, predict microstructural evolution and final mechanical properties under complex thermomechanical schedules. Predicting this microstructural evolution during rolling remains a huge challenge with the conventional mathematical models. Most existing approaches are based on phenomenological descriptions of the kinetics of individual mechanisms such as recrystallization or recovery and require a large number of empirical parameters. These parameters often depend on steel grade, strain path, and temperature, and must typically be determined through extensive laboratory experimentation. To overcome these limitations, we propose an innovative physically based approach that is focused on evaluating the work hardening of the workpiece within the roll gap, thereby constructing an incremental plasticity model capable of describing the stress-strain path of the material in real time throughout the rolling process. This model enables to describe the deformation history and microstructure evolution during the whole thermomechanical process. By shifting the focus from fitting numerous phenomenological parameters to capturing the physical deformation behavior directly in the roll gap, the model enables a more robust and transferable prediction of microstructural evolution. Its application to hot rolling processes (plate or strip) offers significant practical advantages. These include:

1. Real-time tracking of the thermomechanical path,
2. Detection of hardening and softening transitions,
3. Evaluation of retained strain between passes,
4. Identification of the no-recrystallization temperature,
5. Prediction of grain size evolution (both austenite and ferrite),
6. Design and control of optimized rolling schedules for advanced TMCP (Thermo-Mechanical Controlled Processing) products.

The goal of the proposed theoretical approach is to develop a general and adaptive process control framework, referred to as *Smart Rolling*, capable of online monitoring of the hot rolling process and a tool enabling the inference of fine metallurgical aspects of the material behavior directly under industrial processing conditions.

CALCULATION OF WORK HARDENING IN HOT ROLLING PROCESS

The proposed approach starts from the Orowan's differential equation describing the longitudinal equilibrium of the forces operating in the roll bite. Specifically, this equation connects the radial roll pressure, S, at any point on the arc of contact with the horizontal force, f, on the corresponding plane element of unit width, perpendicular to the direction of rolling.

$$\frac{df}{d\vartheta} = 2R'(S\ sen\vartheta \pm \tau\ cos\vartheta) \qquad (1)$$

where R' is the deformed roll radius, S is the radial specific roll separating force, τ is the friction force and ϑ is the angular coordinate in the roll bite. The minus sign refers to entry side and the plus sign refers to the exit side with respect to the neutral plane. The above equilibrium equation contains two unknown functions, i.e. the horizontal pressure for unit width f, and the radial pressure on the roll surface S. To find a unique solution we need to use a second relationship between the horizontal and vertical compressive stresses given by the Huber-Mises plasticity condition:

$$q - \frac{f}{h} = \sigma \qquad (2)$$

In which σ represents the equivalent stress for compression yielding of the material, q is the normal roll pressure and h is the local thickness of the slab. As deeply described in [1] and [2] the work hardening of a workpiece in hot rolling process, under well defined boundary condition at the roll-strip interface (sticking friction condition and plane strain), can be evaluated by the following equation:

$$\frac{d\sigma}{d\varepsilon} = \Omega(\mathbf{p})\sigma \qquad (3)$$

In which σ is the equivalent stress in the material and Ω(p) is the function defined in the roll bite as:

$$\Omega\,(\mathbf{p}) = \left\{\frac{\pm h_o}{\left[2\left(1-\frac{S+t_i}{\sigma}\right)\pm\vartheta\right](2R'+h_o)\vartheta}\right\} \qquad (4)$$

In which the parameter **p** {R’,t,ε,μ} are respectively the deformed roll radius, plate thickness, strain in the roll gap, Coulomb friction coefficient. The above equation represents an explicit relationship between the work hardening properties, the global boundary conditions and the strip geometry of deformation zone. This equation recalls the Considère condition for the onset of plastic instability under uniaxial stress state. It is noteworthy that this condition is valid also for a plane strain compression stress state. This means that the plastic stability of the rolling process depends on the value of Ω and for this reason we call it “stability function”. If $\Omega \geq 1$ the rolling process is stable, conversely if $\Omega < 1$ the rolling process is unstable and local necking could occur. Unstable plastic flow can be a quite critical situation during metal work processing. It is well recognised that, depending on the mode in which the necking and then failure appears, there are two distinct ways that it is noteworthy to mention: diffuse necking beginning and local necking. In tensile tests these two stages are distinctly separated and typically the first one start when work hardening cross the actual true stress-strain curve, and it can be less critical because it is not yet localised on the specimen length. The local necking, instead, occurs on a narrow band in which the deformation can proceed only by thinning and this condition occurs when work hardening is equal to the shear strength of the material. In plane strain deformation the situation is more critical because the local necking occurs very close to diffuse necking condition, i.e. when work hardening cross the true stress value, or $\frac{d\sigma}{d\varepsilon} = \sigma$. The integration, on the contact arc, of the equation (3) leads to calculate the flow stress and work hardening on each mesh element of the roll bite as:

$$\sigma(\varepsilon,\mathbf{p}) = \sigma_{entry} exp(\bar{\Omega}(\mathbf{p})\varepsilon) \qquad (5)$$

$$\frac{d\sigma}{d\varepsilon} = \bar{\Omega}(\mathbf{p})\sigma_{entry} exp(\bar{\Omega}(\mathbf{p})\varepsilon) \qquad (6)$$

Where σ_{entry} is the yield at entry roll bite under plane strain and $\bar{\Omega}$ is the mean integral of $\Omega(\vartheta)$ on the contact arc. The above equations suggest, first of all, that the work hardening depend not only by total strain but also on the stress-strain path and deformation geometry features through the function Ω. Generally, in literature the workpiece hardening behaviour is phenomenologically described by the Swift equation $\mathrm{Y} = \mathrm{Yo}(1+\mathrm{B}\varepsilon)^n$, where B and n are material parameters. It is noteworthy that the hardening behaviour predicted by the above equation and the Swift model are very close (figure 1).

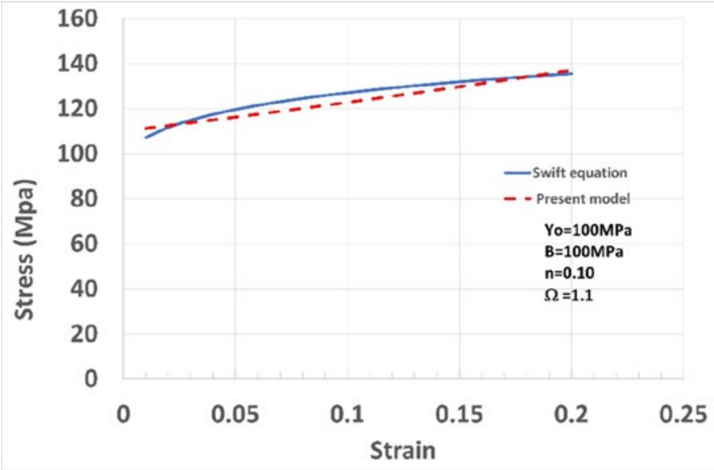


Fig.1 - Comparison between Swift hardening model and the present hardening model.

INCREMENTAL PLASTICITY APPROACH IN SMART ROLLING MODEL

During real time operation the model, schematically represented in figure 2, allows to determine whether the material is in a condition above or below the non-recrystallization temperature (T_NR). If no recrystallization occurs (temperature is below T_NR) the material accumulates the total strain applied during the rolling pass. The microstructure continues to harden through work hardening mechanisms. If recrystallization takes place the Smart Rolling model must further assess the type of recrystallization occurring i.e DRX or SRX. It is noteworthy that dynamic recrystallization (DRX) and Static Recrystallization (SRX) are significantly different in terms of stress-strain path in the roll bite and this produces different work hardening behaviour.

The calculation of the work hardening in real time is described in the following steps. The basic incremental equation for the i-th rolling pass is:

$$\sigma_{eq}(T,\, \varepsilon_i,\, \dot{\varepsilon}) = \sigma_y(T,\, \dot{\varepsilon}) + \Delta\sigma_{WH}\,(T, \varepsilon_i,\, \dot{\varepsilon}) \tag{7}$$

In which $\sigma_{eq}(T,\, \varepsilon_i,\, \dot{\varepsilon})$ represents the equivalent stress calculated at the i-th rolling pass, $\sigma_y(T, \dot{\varepsilon})$ is the yield stress of the material under processing at the strain rate $\dot{\varepsilon}$ and temperature T evaluated according the model reported in [2].

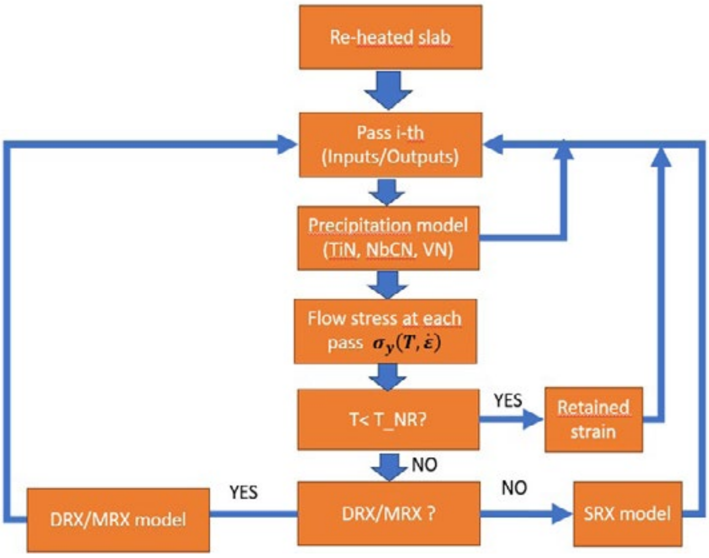


Fig.2 - Schematic view of the real time "Smart Rolling" model.

The total work hardening $\Delta\sigma_{WH}\,(T,\varepsilon_i,\,\dot{\varepsilon})$ represents the cumulative hardening occurring in the strip/plate, after "i-th" rolling pass i.e.:

$$\Delta\sigma_{WH}(T,\varepsilon_i,\,\dot{\varepsilon}) = \sum_j^{i-1}\Delta\sigma_R(T,\varepsilon_j,\,\dot{\varepsilon}) + \left(\frac{d\sigma}{d\varepsilon}\right)_i \varepsilon_i \qquad (8)$$

Where the first term, $\Delta\sigma_R$, is the residual work hardening (due eventual retained strain from the previous passes), and the second term, $\left(\frac{d\sigma}{d\varepsilon}\right)_i$, is the instantaneous work hardening of the i-th pass calculated with the equation (3). With this approach it is possible to reconstruct the stress-strain path of the workpiece in rolling process and therefore to detect, for each rolling pass, the occurrence of softening mechanisms due to dynamic/metadynamic/static recrystallization or hardening mechanisms related to retained strain. Of course, it must be considered that there are additional metallurgical factors affecting the hardening: these are the grain size refinement due to recrystallization and, in case of microalloyed steels, (Nb,Ti)N precipitation. Nevertheless, it must be considered that both hardening effects, in the experimental conditions tested, are significantly smaller than dislocation hardening. Introducing the parameter hardening ratio defined as $\frac{\Delta\sigma_R}{\sigma_y(T,\,\dot{\varepsilon})}$, the occurrence of hardening or softening at the i-th pass of the rolling schedule is evaluated according with the following conditions:

$$\text{Hardening Ratio}=\frac{\Delta\sigma_R}{\sigma_y(T,\,\dot{\varepsilon})} > HR \rightarrow \text{Hardening} \rightarrow \varepsilon_{total} = \varepsilon_i + \varepsilon_{retained} \qquad (9)$$

$$\text{Hardening Ratio}=\frac{\Delta\sigma_R}{\sigma_y(T,\,\dot{\varepsilon})} \leq HR \rightarrow \text{Softening} \rightarrow \varepsilon_{total} = \varepsilon_i \qquad (10)$$

The constant HR, typically fixed in the range 0.1-0.2, represents the threshold separating the hardening and softening of microstructure. The strain path is reconstructed incrementing, if hardening is occurring in the pass, the strain of the actual pass to previous hardening passes. Conversely the strain in microstructure is equal to i-th strain pass.

Model Inputs

In order to evaluate the microstructural evolution and final mechanical properties during hot rolling, the model requires a comprehensive set of inputs that describe both the intrinsic material characteristics and the processing conditions as: chemical composition, reheated austenite grain size, reheating temperature, rolling pass process data (among other rolling force, strain pass, strain rate, temperature).

Model Outputs

The model yields two categories of results:

1. In-Process Microstructural Evolution
    - Flow stress as a function of temperature $\sigma_y(T,\,\dot{\varepsilon})$.
    - Average grain size and retained strain above Tnr
    - Average grain size and retained strain below Tnr
    - Precipitated fraction of microalloying elements Ti, Nb, V.
    - Solid solution concentrations of C and N.
2. Final Microstructure and Mechanical Properties
    - During rolling: 2D distribution of austenite and ferrite grain size
    - After cooling: Phase fractions and distributions (ferrite, pearlite, bainite, etc.)
    - Pearlite interlamellar spacing
    - Yield stress, ultimate tensile strength, and ductile-brittle transition temperature.

Optimized Hot Rolling Schedule

The optimized hot rolling schedule are calculated by means of a machine learning model trained on the database containing the extensive hot rolling process data, microstructural characteristics during rolling passes, and final mechanical properties. The model is then validated and optimized to ensure accurate predictions and generalization. Therefore, the predictive part of smart rolling model allows to define the optimal rolling schedule for each combination of steel quality and plate format in terms of:

√ Number of passes & strain per pass.

√ Roll Speed. This determines the average strain-rate, torque and power needs.

√ Interpass Time. The duration between successive passes controls any microstructural transformations (e.g., static recovery, partial recrystallization) occurring between deformations.

√ Cooling Conditions. The rate of cooling in the run-out table and the coiling temperature determine the type and fraction of phase transformations (e.g., pearlite vs. bainite) that occur after the final pass.

SMART ROLLING APPLICATION

The basic implementation of the "smart rolling" model at the hot rolling mill of Marcegaglia Plates started in offline mode and represented an experimental phase only for the post evaluation of the product quality and calculation of the microstructural evolution of the plate products. In the second industrial step, started on 2025, the smart rolling was developed with a dual mode architecture in order to operate both in real time and in off-line mode for rolling schedule calculation for each plate and with an automatic software for the reinforced training of the model parameters (figure 2-3).

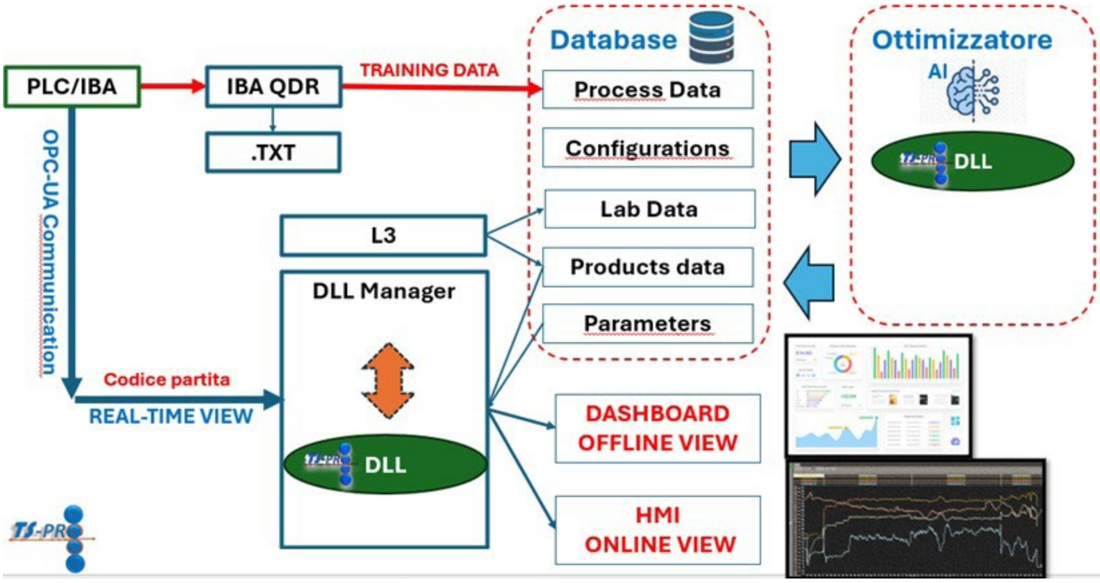


Fig.3 - Smart Rolling dual mode architecture: real time view and offline training of the model parameters.

The scope of the application of the smart rolling is to increase the plant productivity (reducing the rolling pass) and to improve the energy efficiency of the process, carrying out a proper design of the number of passes in softening stage and reducing the pass in the hardening stage where the higher work hardening and power are needed. The hot rolling plant consists of a quarto reversible mill with maximum plate width of 3000mm. The metallurgical investigation was focused on the work hardening behaviour of microalloyed steel (table 1) during hot rolling process, on the Nb effect on hindering the recrystallization kinetics and finally on the effect of retained strain of the austenite phase as key parameter to evaluate the final product properties (no accelerated cooling was used). As it is well documented in literature the importance of retained strain during the hot rolling process is attributed to the effect of pancaked austenite microstructure to encourage the production of a predominantly fine polygonal ferrite forming during the austenite decomposition in the plate cooling stage. In the proposed approach the retained strain ε_r is evaluated as the cumulative strain starting from the pass from which the workpiece increases the residual hardening $\Delta\sigma_R$. With this approach the stress-strain path of the workpiece, associated to the applied hot rolling schedule, can be reconstructed. The application of the model allows to detect quite directly the rolling passes in which softening or hardening occurs during the hot rolling process (figure 4). In particular, the last rolling pass at which occurs softening is considered an evaluation of the temperature of no recrystallization.

Tab.1 - Steel chemical composition of the industrial plates considered in experimentation.

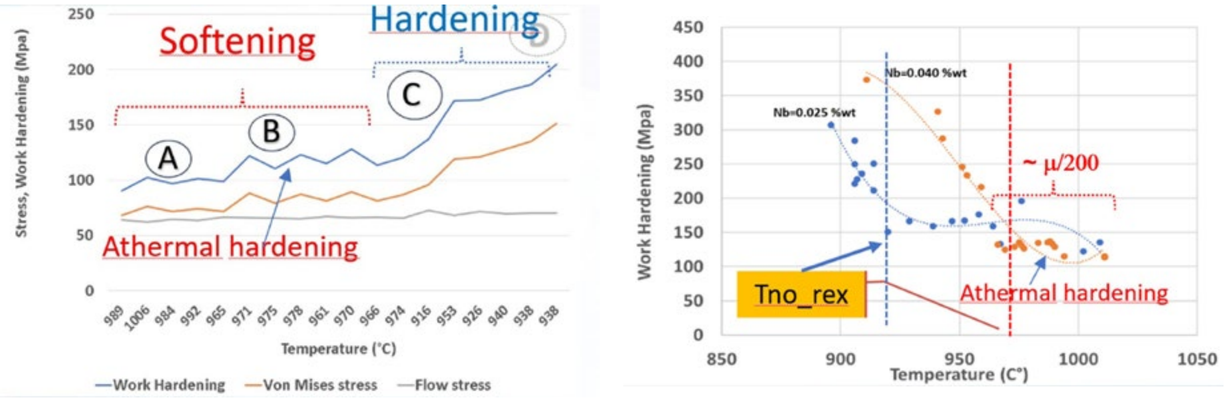
Steel grade	C (wt%)	Mn (wt%)	Si (wt%)	Nb (wt%)
S355J2	0.15-0.17	1.45-1.50	0.18-0.22	0.025-0.045

The main metallurgical novelty of the proposed approach is the implementation of the work hardening as an additional pillar for the design of hot rolling schedule. This power demand from the process is strictly related to the yield strength in the roll bite and this is influenced by the strain hardening behaviour, strain path, strain-rate, temperature profile and precipitation behaviour. As a further benefit, this approach should reduce the risk of non-homogeneous deformation on the strip width and on longitudinal direction.

The power needed for hot rolling process is evaluated as the product of the torque, i.e. the moment of the tangential forces in the arc of contact about the roll axes, times the angular speed, i.e.:

$$P = 2\omega R R' k Q_G(R'/h, r)$$

in which k is the effective yield stress of workpiece in the roll bite (equation 5) and $Q_G(R'/h, r)$ is a numeric function accounting for the effect of the deformation geometry features on the deformation energy demand.



a) b)

Fig.4 - a) Typical Work hardening behaviour in hot rolling; b) work hardening behaviour during hot rolling of plates with different Nb content (S355J2 steel).

In terms of work hardening behaviour, the general trend reveals the occurrence of 4 stages. Depending on initial and final rolling temperature the stage I or IV can be less pronounced or almost absent. The first stage, occurring at higher temperature (T>960°C), is characterised by low work hardening (≤120MPa) and with the equivalent stress very close to flow stress. In this stage the softening mechanisms are dominant and the microstructure, at each pass, is refined by recovery/recrystallization. The second stage is characterised by work hardening in the range 150-200 MPa increasing with a slow rate. In this stage it can be detected the effect of Niobium in retarding the recrystallization between two consecutive passes. In the third stage the work hardening increases with a higher rate and, depending on the chemical composition and temperature, it can achieve quite high value. Occasionally it could be detected a fourth stage characterised by a saturated or decreasing work hardening behaviour. The comparison of work hardening of two plates with different Nb content (figure 4b) also reveals that, higher Nb content anticipate the stage III at higher temperature (no recrystallization temperature). The austenite grain size for each recrystallization step is calculated according with the Sellars approach [1-2-10] adopting the uniform softening method, wherein kinetics are forecasted based on a singular average microstructure with an effective strain. In case of hardening, wherein no recrystallization or recovery takes place, the strain associated to the current pass is considered as retained within the microstructure. The application of this method allows to reconstruct the evolution of the austenitic grain and to calculate the ferritic grain size, below the Ar3 temperature, accounting for the pancaking effect of the austenitic grain during hot rolling. The final step consists in the calculation of the tensile properties of the final product (yield stress and tensile strength) using empirical equations and the ML model developed based on the historical industrial results. In the figure 5-6 are shown respectively the results of the mathematical model, in terms of ferritic grain size and yield stress for a S355J2 plate. Each plot gives the distribution along the thickness at each pass of the hot rolling schedule. The grain size is evaluated according with the method described in [1] and [2]. The soundness of the results is evaluated thanks to comparison between the calculated tensile properties (yield stress and tensile strength) with the room temperature tensile test results. The validation of the approach and the evaluation of the errors on the calculated grain size and tensile properties are under quantitative evaluation and represent a consistent part of the ongoing work to be done.

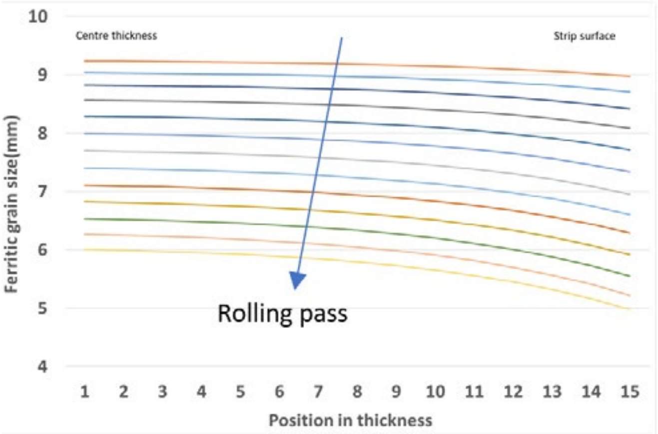


Fig.5 - Ferritic grain size evolution during hot rolling schedule (S355J2 plate).

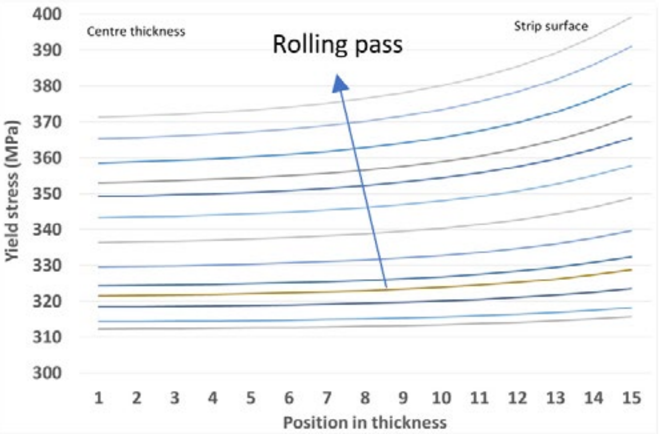
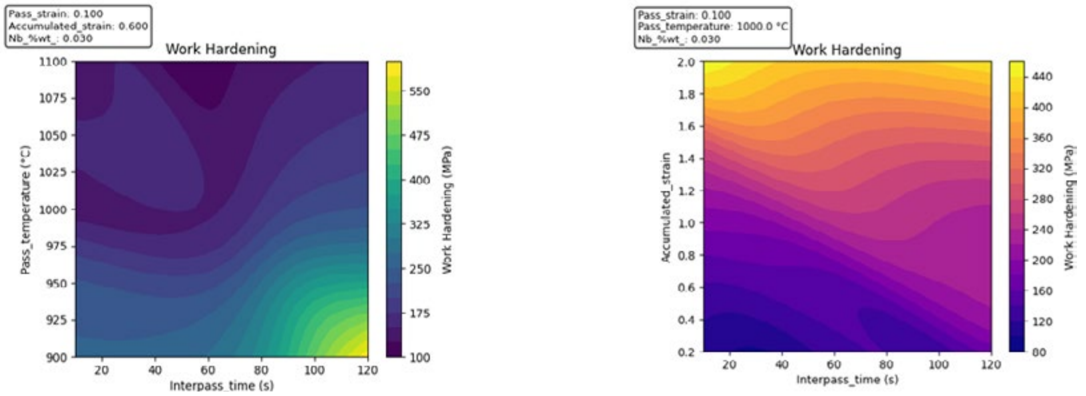


Fig.6 - Yield stress evolution during hot rolling schedule (S355J2 plate).

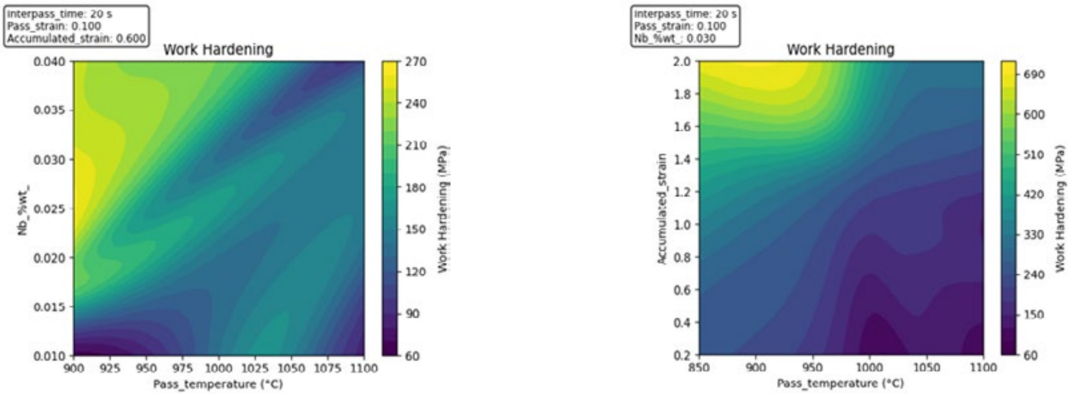
Due to strong inter-dependence of the rolling process variables, to discern the single variable effect on work hardening behaviour and on plastic stability of the global process it was developed a dedicated machine learning model trained on the database of smart rolling results. The ML model allows to get a more intuitive visualization of the work hardening behaviour when more than one process parameter is varied simultaneously. In figure 7 a)-b) and figure 9 a)-b) are shown the work hardening behaviour relevant to hot rolling process data of more than 1000 plates of microalloyed steel grade S355J2. In particular, in figure 7 is shown how the work hardening is affected by a variation inter-pass time, temperature and retained strain. In figure 8 is shown how the work hardening is affected by a variation of chemical composition (Nb content), temperature and retained strain.



a) b)

Fig.7 - a) Work hardening as a function of pass temperature and interpass time; b) Work hardening as a function of retained strain and interpass time (S355J2).

The aim of this approach is to design the rolling pass schedule in steady conditions avoiding processing windows in which non homogenous work hardening properties could induce a not homogeneous plate deformation and of consequence also microstructure and flatness issues. In figure 9-b) the Tno_rex becomes clearly detectable at low levels of accumulated strain when the work hardening increases from 50–150 MPa to 200 MPa or more.



a) b)

Fig.8 - a) Work hardening as a function of pass temperature and interpass time; b) Work hardening as a function of retained strain and interpass time (S355J2).

Plastic stability in hot rolling

As discussed above, equation (3) could provide important insights into the plastic stability of the hot rolling process. This approach opens up both theoretical and practical novel frontiers. From a theoretical perspective, equation (3) suggests that the plastic stability of hot rolling deformation is significantly affected by deformation geometry and roll-workpiece boundary conditions, particularly friction. From an application standpoint, optimizing the plastic stability associated with proper operational windows could improve the overall power demand of each rolling schedule. Achieving this ambitious goal requires optimizing both the softening and hardening passes and, more importantly, addressing the friction behavior in the roll gap. It is well recognized that modifying the friction conditions in the roll gap represents a significant challenge because, until now, there have been no theoretical approaches to predict the behavior of the rolling process. The proposed approach aims to define the foundations for this methodology.

The general solution of the equation (3) is:

$$\sigma(\varepsilon,\mathbf{p}) = \sigma_{entry} exp(\overline{\Omega}(\mathbf{p})\varepsilon)$$

This defines an 4-dimensional hypersurface in a 5-dimensional space in which the parameters **p** $\{R', t, \varepsilon, \mu\}$ are respectively the deformed roll radius, plate thickness, pass strain, friction coefficient.

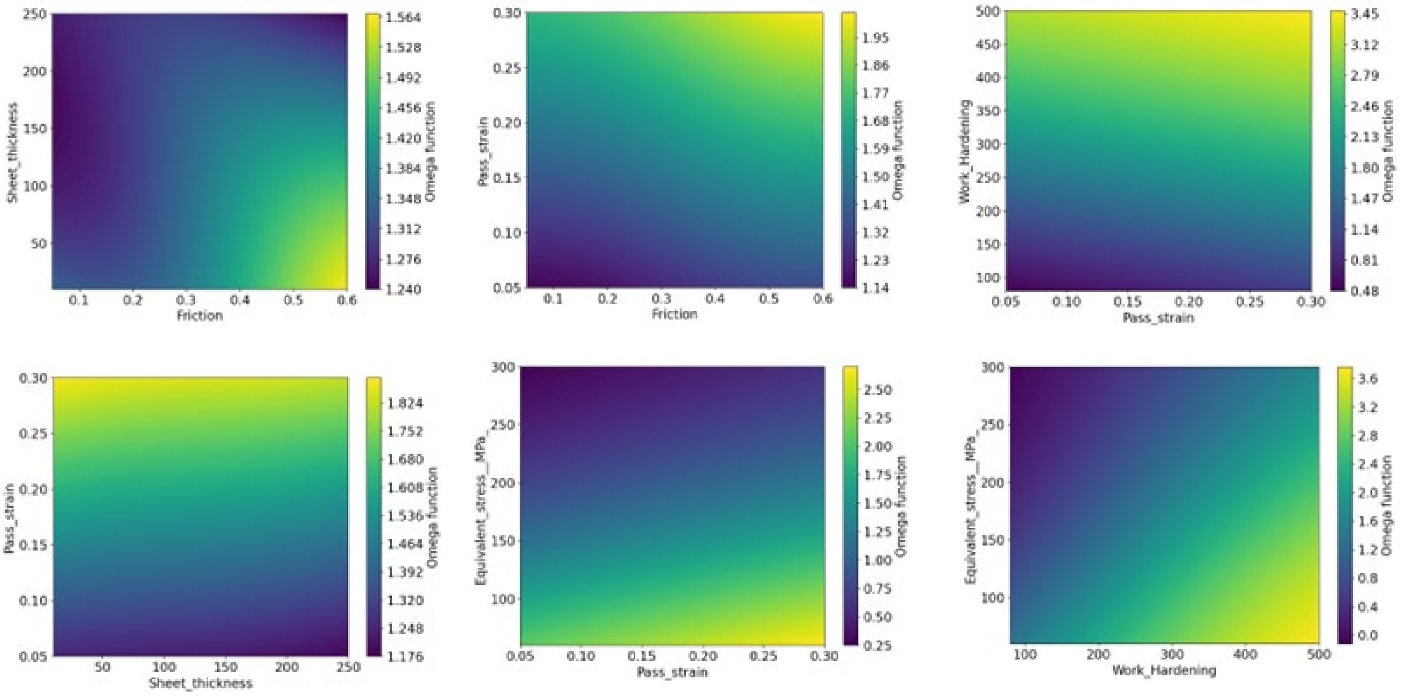


Fig.9 - $\Omega(\mathbf{p})$ in terms of main hot rolling process parameters.

Since σ and Ω are exponentially linked, we can get more insigths by looking directly at mapping $\Omega(\varepsilon,\mathbf{p})$ to see how the stability function changes. To better visualize and explore this 4-dimensional object, the most practical approach is to choose two varying parameters, fix all the others, and then plot a 2D contour/color map at a fixed strain. Figure 9 presents a series of plots that illustrate how the function Ω, and consequently plastic stability, varies with changes in the main process parameters. Ω values closer to unity indicate that the plasticity conditions are near to instability, suggesting an higher sensitivity to anomaly occurrence. Notably, a lower friction coefficient has a pronounced adverse effect on plastic stability, especially at small strain reductions. Conversely an higher friction coefficient could enhance the plastic stability, thereby reducing the risk of instability and failure. These plots provide valuable insights into the relationship between friction and plastic stability. This highlights the critical role of friction in maintaining the stability of the hot rolling process. Understanding this relationship is essential for optimizing the rolling process and preventing potential issues.. This insight could be pivotal in developing strategies to optimize the rolling process, ensuring better control over the deformation and improving the overall efficiency and reliability of the operation.

CONCLUSIONS

In this paper, we propose a novel methodology based on incremental plasticity approach aiming to get deeper insights about into metallurgical phenomena governing the hot rolling process. The method consists in gathering the work hardening rate plot (occurrence of discontinuity, rate changes) from the real-time hot rolling process. These data were used to infer, thanks to last generation generative AI models, the most important metallurgical features such as plastic instability conditions, no-recrystallization temperature, softening/hardening contributions of each rolling pass and retained strain at each stage. The prediction of final grain size and tensile properties (yield strength and ultimate tensile strength) on the plate length and through thickness is qualitatively quite good. Quantitative validation of the methodology, together with a systematic assessment of prediction accuracy and associated uncertainties, is currently under investigation and will be the subject of forthcoming publications.

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