TENSIL-PRO: from tensile properties calculation to incremental plasticity applications

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Tensil-Pro is a mathematical model able to evaluate in real time the tensile properties, in terms of yield stress, tensile strength, uniform elongation, elongation to rupture and additional important microstructural features such as grain size and recrystallized fraction. Tensil-Pro can be applied to all steels: single phase, multi-phase, ferritic and austenitic. In addition it can be applied also to other metallic alloys such as aluminium and copper. The basic approach starts from the Orowan equilibrium equation describing the rolling pressure distribution along the contact arc at the roll strip interface in the form of a differential equation and describing the rolling process in terms of the interaction of 3 main components: the work rolls, the lubricant and the workpiece. The material properties and the roll strip interaction are evaluated by means of a set of original constitutive equations whose parameters are determined with a self-training algorithm that need not laboratory tensile test results. Very recently was proposed a novel physical approach [5] to calculate the work hardening of metals undergoing a rolling deformation process (both hot and cold) on the basis of the rolling process parameters. The description of the evolution of microstructure in deformation process depending on the loading/straining history, as for example in hot rolling, requires the knowledge of the work hardening during each deformation step. The work hardening represents therefore the key enabler factor to build an incremental plasticity model able to describe, in real time, the evolution of microstructure, design the optimized rolling schedule and finally to realize a smart rolling process.

KEYWORDS: WORK HARDENING, INCREMENTAL PLASTICITY, STRAIN PATH, SMART ROLLING

INTRODUCTION

Historically the main aim of the mathematical modelling of the rolling process, from the first model published more than 90 years ago, when von Kármán initiated the slab method [1], was, above all, the calculation of the rolling forces for the dimensioning of the stands, secondarily for the motors torque and power design. The mathematical model proposed in the present paper, Tensil-Pro, reversed the aim of the classic rolling modelling: the rolling force distribution, entry/exit tension and strip geometry in roll bite are input data of the model while the output values are the flow stress and work hardening of the workpiece. The friction force is introduced as a roll-strip boundary conditions with a friction coefficient assumed constant on the contact arc. The flow stress is evaluated on the basis of the stress

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balance on the differential slab considering the friction hill in the roll bite. The theoretical background of the Tensil-Pro to evaluate the work hardening is strictly related to the properties of the stress tensor. In plane strain conditions, the normal stress distributions can be calculated, without any knowledge of the deformations occurring in roll bite [2], from the general equilibrium conditions of the forces acting in roll bite (both vertical and longitudinal direction) together with the Huber–Mises plasticity condition. This favorable circumstance was exploited to define, as described in the next section, an analytical relationship between flow stress, work hardening and strip geometry in roll bite.

TENSIL-PRO MODEL: MATHEMATICAL APPROACH

Work hardening distribution in roll bite

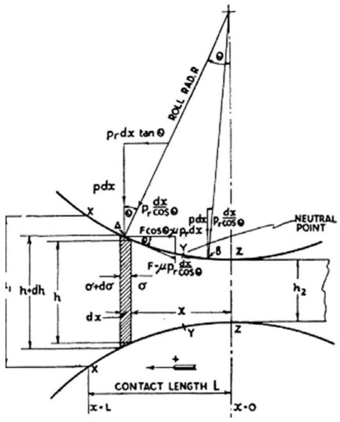

Fig. 1 - Roll bite geometry.

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The tensil-pro approach for work hardening calculation is based on a relationship found, for plane strain conditions, between work hardening, flow stress and strip deformation geometry in roll bite. This represent a quite new approach that does not make use of the microscopic level of deformation but only concepts of the continuum mechanics and the classic Orowan rolling theory [2]. This methodology and its application in rolling process was recently filed for a patent application [7]. The theoretical approach start from the force equilibrium condition in longitudinal direction on a slab element (Figure 1):

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

where R′ is the deformed roll radius, S is the radial specific roll separating force, μ is the Coulomb friction coefficient 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 vertical compressive stress q is related to radial force S by the following equilibrium equation

$$q = S \mp \mu S\, tan\vartheta \qquad [2]$$

The above equilibrium equations contains 3 unknown functions, i.e. the horizontal pressure f for unit width, the radial pressure S and vertical pressure q. To find a unique solution the classic approach introduces a second relationship between the horizontal and vertical compressive stresses given by the Huber-Mises plasticity condition

$$q - \frac{f}{h} = \sigma \qquad [3]$$

In the above equation σ represents the compression yielding of the material and h is the local thickness of the slab. The mechanical equilibrium along the RD can be written, after some algebra reported in [6], in terms of normal pressure S, flow stress, work hardening and strip geometry in roll bite as follows: [4]

$$h\frac{d}{d\vartheta}(S \mp \tau\, tan\vartheta - \sigma) + (S \mp \tau\, tan\vartheta - \sigma)\frac{d\,h}{d\vartheta} = 2R'(Ssen\vartheta \pm \tau cos\vartheta)$$

Changing the derivative from angular variable ϑ to true strain, multiplying by $\frac{d\,h}{d\vartheta}$ and considering that the local strip thickness can be expressed as $h = h_o + 2R'(1 - cos\vartheta)$, after few algebra steps the equation (4) can be written as:

$$\frac{d\sigma}{d\varepsilon} - \sigma = \frac{dS}{d\varepsilon}(1 \mp \mu\, tan\vartheta) \pm \frac{\mu S(h_o + 2R')}{R' cos\vartheta\, sin2\vartheta} \qquad [5]$$

The above equation (5), assuming S represented by Bland Ford function represents a relationship between work hardening a flow stress within the roll bite. This approach represents, at the knowledge of the authors, a new and quite interesting way to achieve important results in terms of calculation of work hardening in roll bite and application of an incremental plasticity model in rolling process. With this assumption the derivative $\frac{dS}{d\varepsilon}$ it is calculated accordingly:

$$\frac{dS}{d\varepsilon} = -S\left(1 \pm \frac{\mu}{\vartheta}\right) + \frac{S}{\sigma}\frac{d\sigma}{d\varepsilon} \qquad [6]$$

Substituting the equation (6) within the (5) it is found after some algebra the following equation:

$$\frac{d\sigma}{d\varepsilon} = \Omega\sigma \qquad [7]$$

In which Ω, named stability function, in case of slipping friction condition is defined as:

$$\Omega = \left(1 + \mu^2 \frac{1 \pm \frac{h/2R'\vartheta}{\mu}}{\left(\frac{\sigma}{S} - 1\right)\left(1 - \frac{1}{2}\vartheta^2\right) \pm \mu\vartheta}\right) \qquad [8]$$

It is noteworthy to underline that the equation (7) is derived with the slipping roll-strip boundary conditions. The same approach can be applied also for sticking boundary conditions leading to a different expression for Ω function [5]. The equation (7), in addition to state that in rolling process the flow stress and work hardening are related each other, has many important implications on deformation stability in rolling process (stable if $\Omega \geq 1$). The detailed analytical derivation of this relationship and the discussion of its implications on the stability of rolling deformation as a function of strip deformation geometry and rolling process parameters (friction coefficient, roll radius, entry-exit tension) are discussed in a quite recent paper [5]. The integration, on the contact arc, of the equation (7) leads to the following results:

$$\sigma = \sigma_o exp\left(\int \Omega d\varepsilon\right) \qquad [9]$$

$$\frac{d\sigma}{d\varepsilon} = \Omega\sigma_o exp\left(\int \Omega d\varepsilon\right) \qquad [10]$$

Where σ_o is the yield at entry roll bite. The equation (10) can be integrated easily with Matlab toolbox. It highligths that the work hardening depend, through the function Ω, not only on total strain but also on the strip boundary conditions (friction, entry/exit tension) and the strip geometry in roll bite.

YIELD STRESS ONLINE EVALUATION

The flow stress of the strip is evaluated starting from equation (3) through several mathematical steps. At the first step is calculated the roll pressure as a function of angular variable assuming a slipping friction boundary conditions (lubricated roll conditions). The work hardening of the strip is added in a later stage. The second step consists in the evaluation of the average roll pressure on the roll bite. The third step consists in reversing this equation: the flow stress of material as a function of the applied roll force, strip deformation geometry and other process parameters is obtained. The calculated flow stress is related to friction coefficient and for this reason this aspect requires a special attention. The friction coefficient is continuously calculated adopting a standard approach but a specific model parameter is associated in order to control and monitor eventual deviations of the cold rolling process. The adopted approach allows the Tensil-Pro to be quite reliable and very sensitive to strip metallurgical characteristics: grain size, second phases, precipitation pattern and so on. This guarantees an high sensitivity to HDG process conditions (speed line, soaking temperature) if Tensil-Pro is installed in skin pass, and an high sensitivity to hot rolling process conditions if the Tensil-Pro is installed in the first stand of cold rolling mill. At this stage the calculated flow stress is dynamic in the sense that is referred to the actual strain rate adopted in the process. So the value must be scaled up to the quasi-static conditions (about $10^{-4}s^{-1}$) adopting the well-known constitutive approach. The tensile strength and then uniform elongation and total elongation are evaluated thanks to original constitutive equations and specialized to each steel grade by means of model parameters.

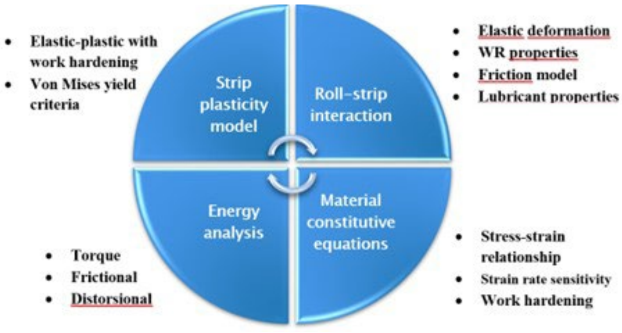

Fig.2 - Tensil-Pro model structure.

TENSIL-PRO RESULTS: ONLINE EVALUATION OF TENSILE PROPERTIES

HDG steel products

The evaluation of tensile properties on the whole length of the galvanised coils is carried out adopting the Tensil-Pro model installed on the PLC of the skin pass. At Ravenna plant Tensil-Pro is installed on all the 4 hot dip galvanising lines. In the figure 3 is reported the results of Tensil-Pro in terms of tensile strength (Rm) obtained on galvanising line n.4 compared with tensile test results for different steel grades. As it can be noted for all the steel qualities the agreement is significantly better than ±10%.

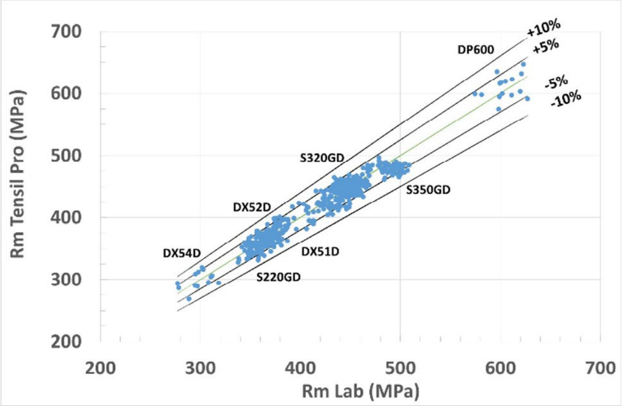

Fig.3 - Tensil-Pro performance on HDG products in terms of tensile strength

Hot rolled carbon steel

The evaluation of tensile properties on the whole length of the hot rolled coils is carried out adopting the Tensil-Pro model in the first stand of the cold rolling mill. At Ravenna plant, Tensil-Pro is installed in 2 reversible mills (double stands) and 1 Tandem mill (5 stands). In figure 4 are reported the average tensile properties, in terms of yield stress and strength, of the whole product mix of the tandem mill. It is interesting to note that the hot rolled coils were produced by several steel works with significant process differences. The plot of figure 4 is very helpful to evaluate the statistical homogeneity and for benchmarking of the tensile properties of hot bands produced by different steelworks.

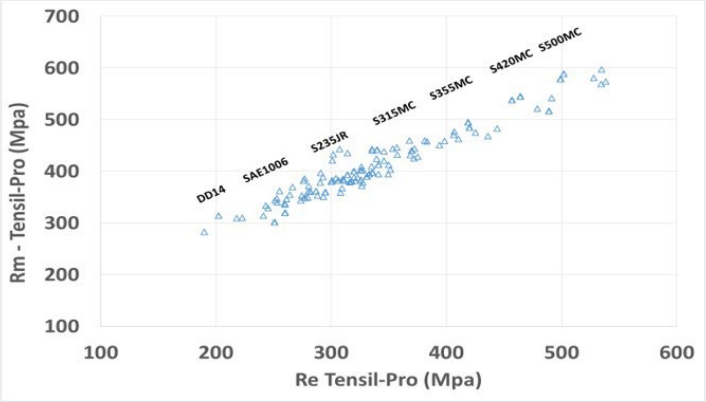

Fig.4 - Hot rolled coil tensile properties calculated by Tensil-Pro.

Stainless steel grades

Tensil-Pro represents, at moment, the only industrial system able to evaluate online the tensile properties of both austenitic and ferritic stainless steels. In the figure 5 are reported the industrial results of Tensil-Pro obtained on AISI304 stainless steel grade compared with laboratory tensile test results obtained on the annealing and pickling line n.2 of Marcegaglia Gazoldo plant. In this case the Tensil-Pro model is installed in the PLC of the skin pass of the line. As it can be noted the agreement is within the ±10% for both yield stress (Re) and much better for tensile strength (Rm).

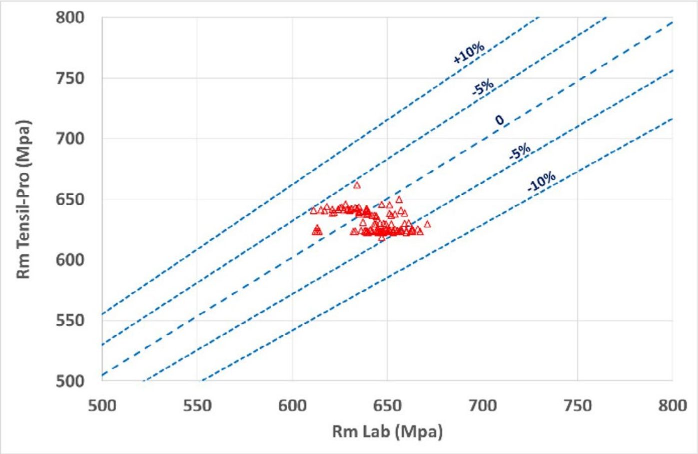

Fig.5 - Tensil-Pro performance on AISI304 in terms of tensile strength Rm.

INCREMENTAL PLASTICITY APPROACH

The mathematical description of a specific deformation process with multi axial stress state can be approached in two different ways: the first is the 'total deformation approach' and, the second is the 'incremental plasticity theory'. The first approach is simpler and should be applied when a relationship between total strain with total stress exist, i.e. no stress history effect can be accounted for. A good field of application of this approach is represented by simple cold deformation processes in which the deformation is consisting of a single o very few deformation step. The incremental plasticity is basically a differential approach in which strain increments are related to stress increment so that the history effect can be accounted for. There is no doubt that the incremental theory of plasticity is more general and more applicable than the total deformation approach but the issue is typically related to higher mathematical and conceptual complexity. It is quite evident that the incremental plasticity is the only theoretical approach usable in high temperature deformation process where, the occurring of softening process together with multi axial stress state, does not allow the application of a simple total deformation approach. Therefore the incremental plasticity theory is based on the need to define an equation that correlates the strain increment to stress increment, i.e. the work hardening. The equation (7) represents the fundamental building block for an incremental plasticity approach to evaluate the microstructure evolution in rolling process. In fact in a multi stage deformation process, the flow stress of the workpiece at the exit of the n-th step is the product of n work hardening terms:

$$\sigma_n = \sigma_o\, exp(\int \Omega_1 \mathrm{d}\varepsilon) * exp(\int \Omega_2 \mathrm{d}\varepsilon) * exp(\int \Omega_3 \mathrm{d}\varepsilon) *\ldots* exp(\int \Omega_n \mathrm{d}\varepsilon) \qquad [11]$$

In which σ_o is the entry flow stress at the first rolling stand and Ω_i are the stability functions of each deformation step (figure 6). The value of work hardening is depending on both stress, stress history and the relevant plot along the roll bite could be not continuous. In fact if we proceed along the roll bite and calculate it by breaking the loading path into segments of different stress mode (plastic loading under tension, compression, unloading under compression and finally tension), in each segment, we can determine $\frac{d\sigma}{d\varepsilon}$ according with equations (9,10,11). In the case of a hot rolling application aiming to follow the microstructure evolution in multi passes rolling process the calculation of total work hardening requires the integration of the terms $\int \Omega_n \mathrm{d}\boldsymbol{\varepsilon}$ on the whole roll bite. The proposed approach is shortly resumed in the following sections.

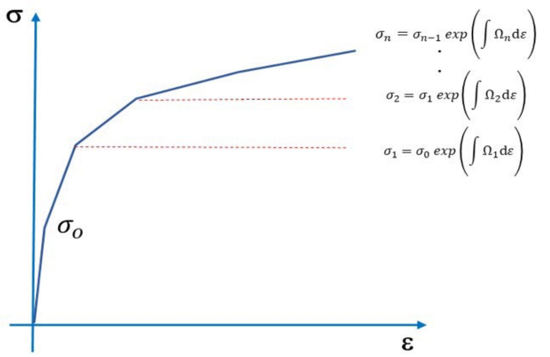

Fig.6 - Incremental plasticity approach thanks to work hardening calculation.

INCREMENTAL PLASTICITY APPLICATION IN HOT ROLLING PROCESS

Detection of softening and hardening

The plastic deformation of austenite is carried out at high temperatures and strain rate and competition between hardening (dislocation storage) and softening (dislocation density reduction) mechanisms occurs. Furthermore the softening mechanisms, recrystallization and recovery, are manifold (static, dynamic, metadynamic) and characterised by quite different kinetics. With the knowledge of the instantaneous work hardening the stress-strain path occurring during the hot rolling process can be reconstructed, premised that the flow stress of workpiece as a function of deformation temperature and the equivalent stress in each rolling pass are calculated [7]. The calculation of the work hardening in real time allows the possibility to adopt an incremental approach and to reconstruct the strain path along the rolling schedule. The basic incremental equation for i-th rolling pass is:

$$\sigma_{eq}(T,\ \varepsilon_i,\ \dot{\varepsilon}) = \sigma_y(T, \varepsilon_i,\ \dot{\varepsilon}) + \Delta\sigma_{WH}\ (T, \varepsilon_i,\ \dot{\varepsilon}) \qquad [12]$$

In which σ_{eq} (T, $\varepsilon_i, \varepsilon^{\cdot}$) represents the equivalent stress calculated at the i-th rolling pass, σ_y $(T, \varepsilon_i, \varepsilon)$ is the yield stress of the material under processing at the strain rate $\varepsilon^{\cdot}$ and temperature T evaluated according [6]. The total work hardening $\Delta\sigma_{WH}$ $(T, \varepsilon_i, \varepsilon^{\cdot})$ represents the cumulative hardening occurring in the strip/plate, after 'i' rolling passes. The total work hardening $\Delta\sigma_{WH}$ $(T, \varepsilon_i, \varepsilon^{\cdot})$ represents the cumulative hardening mechanisms occurring in the strip/plate, after 'i' rolling passes, i.e.:

$$\Delta\sigma_{WH}(T, \varepsilon_i,\ \dot{\varepsilon}) = \textstyle\sum_j^{i-1} \Delta\sigma_R(T, \varepsilon_j,\ \dot{\varepsilon}) + \left(\frac{d\sigma}{d\varepsilon}\right)_i \varepsilon_i \qquad [13]$$

Where the first term is the residual work hardening (due to previous passes), and the second, $\left(\frac{d\sigma}{d\varepsilon}\right)_i$, is the instantaneous work hardening of the i-th pass calculated with the equation (10). With this method it is possible to detect, for each rolling pass, the occurrence of softening mechanisms due to dynamic/metadynamic/static recrystallization or hardening (retained strain).

Hot rolling tests results

The proposed incremental plasticity approach was applied to investigate the evolution of the retained strain and recovery/recrystallization in a plate hot rolling mill (Marcegaglia Plates plant). In table 1 is reported the chemical composition of the microalloyed steel grades selected for the investigation. The hot rolling schedule is characterised by an initial slab thickness of 250mm and a final plate thickness of 70mm. The initial/final temperature are respectively 1030°C / 870°C.

Tab.1 -Steel chemical composition tested in experimentation at Marcegaglia Plates.

C (wt%)	Mn (wt%)	Nb (wt%)	Tno-rex
0.17	1.48	0.024	1060

In the figure 7 is reported the calculated yield stress as a function of temperature according with [6] for the selected microalloyed steel. In the figure 8 is shown the cumulated strain applied (sum of the strain pass), the retained strain along the hot rolling process (strain path) calculated following the approach described above.
In the same plot is reported also the critical strain for dynamic recrystallization ε_c [6]. This plot represent just an example of the application of the proposed approach. As a general trend, microalloyed steel can recrystallize only above the no-recrystallization temperature (T_{no_rex}). At temperature below T_{no_rex} recrystallization could occur only if enough long time is waited. Each point in the plot correspond to a single rolling pass with the characteristic temperature and strain rate. The effect of strain rate is quite evident especially for the last passes in which typically the strain rate reaches 3-4 s^{-1}. In the hot rolling schedule reported in figure 8 the temperature in the initial passes is slightly lower and different interpass time were adopted. These differences in the hot rolling process produced a significantly different retained strain path. In the first 9 passes no accumulation of strain is detected. The result would suggest that recovery is occurring, so during the interpass time the recovery process determined a rearrangement of dislocations leading to a decrease of flow stress. At lower temperature the retained strain increases and no softening seems to occur.

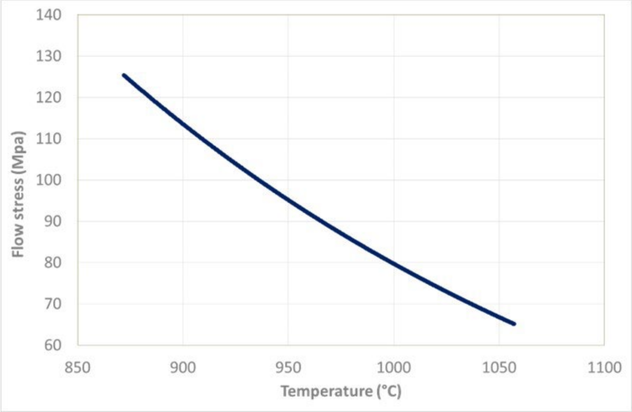

Fig.7 - Flow stress as a function of temperature of the selected microalloyed steel.

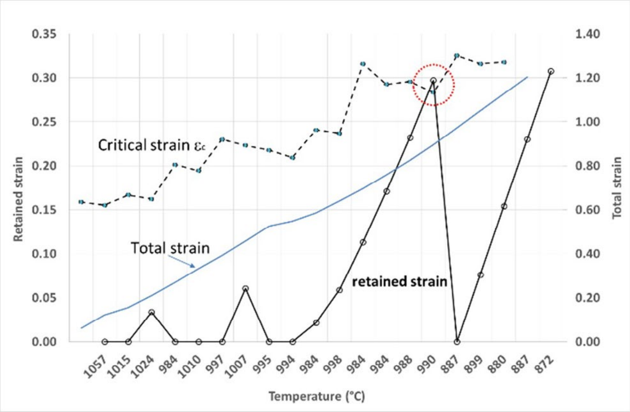

Fig.8 - Retained strain during hot rolling process of microalloyed steel.

The rolling pass in which occurs a drop of retained strain (marked with red circle) is corresponding to a long interpass time (300s) and in this case static recrystallization occurred. This analysis represents an interesting investigation opportunity, i.e. it could make possible to obtain the evolution of the recrystallization/recovery mechanisms and to design the hot rolling schedule (TMCP) with significantly low energy consumption on the basis of reliable industrial results.

CONCLUSIONS

In the present paper it was presented a new methodology for online monitoring of the tensile properties, work hardening, strain path, and microstructure evolution during strip/plate rolling (hot and cold). This approach is applicable to all steels (austenitic, ferritic) and also other alloy systems (Aluminium first of all). The main theoretical results proposed in the paper is that under axially symmetric conditions (plane strain) in rolling process exists a relationship between the work hardening, flow stress and strip boundary conditions in the roll bite (friction, entry/exit tension). The knowledge of work hardening allows to built up an incremental plasticity model approach thanks to which is possible to reconstruct the stress-strain path history quite directly. The evaluation of both work hardening and flow stress as a function of temperature and strain rate, make it possible to discriminate the softening/hardening contribution of each rolling pass and finally to determine the retained strain at each rolling pass. As a corollary it is possible to gather further metallurgical informations to study the role played by alloying elements and other fine metallurgical factors, such as the stacking fault energy (SFE), on controlling recrystallization and work hardening. This methodology applied to hot rolling process appears quite promising to realize a Smart Rolling process in which the smart sensors can be used to evaluate online adjustments to the hot rolling schedule. A further development of this approach could be addressed to the optimization of the energy consumptions related to hot rolling process (slab reheating temperature, steel chemical composition) and to study the strain-rate sensitivity and strip temperature profile on the recrystallization phenomena.

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