

Nidec ASI automation system for a continuous tandem mill coupled with pickling line

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The cold rolling is one of the main sectors for rolling flat products, and a continuous tandem mill is by sure one of the most comprehensive and significant plants in the wide range of the metals industry. A reliable high-performance automation system is consequently indispensable to make the most of the mechanical and hydraulic equipment in a process of this type, that must meet requirements in productivity and quality of the final coil increasingly stringent.

This paper aims to illustrate both the plant and the automation system, focusing on the most significant aspects related to automation developed in the company, from mathematical models to fuzzy regulation algorithms, but without neglecting the global architecture of the system..

Keywords: Rolling - Process Control - Iron Metallurgy - Steel

INTRODUCTION

The history of modern cold rolling began many tens of years ago; automation systems started gradually playing their role, up to increase more and more their importance so to become an indispensable part of the rolling process.

A brief description of the continuous tandem mill coupled with pickling line (Fig. 1), one of the most complex plants in all the metals sector, allows to have a look of the requirements with which today a high-quality final coil must be produced.

The subsequent presentation of the automation layout gives the idea of the system necessary for meeting such strict plant requirements.

The second part of the paper illustrates the different automation levels and supplies some details on the main technological functions and mathematical models, without forgetting to mention the last control improvements.

BRIEF DESCRIPTION OF THE PLANT AND OF ITS REQUIREMENTS

The purpose of a cold rolling mill is to reduce the thickness of the entering coils of steel (coming from a hot strip mill) to a defined target with great accuracy, guaranteeing the best



Fig. 1 - 5-stand tandem mill (PRC)

Fig. 1 - Laminatoio a freddo a 5 gabbie (Repubblica Popolare Cinese)

surface quality of the final strip and high plant productivity: note that a rolling mill usually works 24h/7d.

There are more than one different type of mills able to reach these targets, smaller or larger depending on productivity and final product characteristics. The largest one is composed by a set of rolling stands (usually 5) able to reduce the steel thickness by means of pressure (Fig. 2, rolling force), created by hydraulic capsules and exercised by 2 work rolls on the strip itself; and by means of the tensions between one stand and the others (interstand tensions); 4 or, as in the picture, 6 rolls in total are present in each stand for giving the suitable stiffness to the whole assembly.

The plant in the upper-right corner in Fig. 2 is a coil-to-coil tandem mill: each coil enters the mill, is rolled and is

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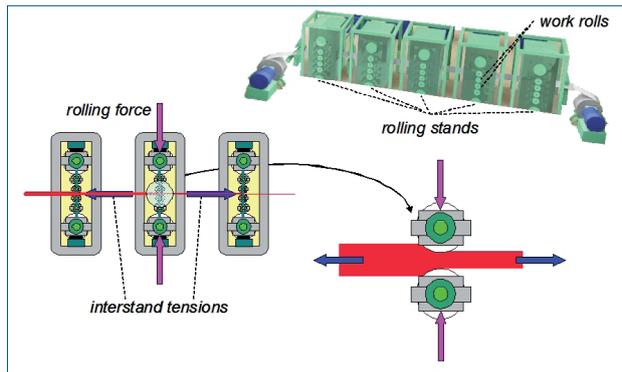


Fig. 2 – Tandem mill applies forces and tensions to reduce the strip thickness

Fig. 2 – Il laminatoio esercita forze e tiri intergabbia per ridurre lo spessore del nastro

extracted when it has finished. Its productivity, in addition to stability of operations, can definitively increase if the coil-to-coil process is transformed into a continuous process by welding the head of a coil to the tail of the previous one (Fig. 3): in this way, the tandem can roll continuously, without stopping and restarting when a coil finishes. Because welding machines require the strip to stop for a while, an accumulator (looper) is necessary in order not to stop rolling at the tandem mill. A flying shear located at tandem exit cuts the strip when a new coil has been formed on the coiler so that the process turns back to be discontinuous.

Much time can pass after hot rolling and before cold process, rust is formed on the metal and it must be eliminated from the surface of the strip before it is rolled by having the strip passed inside tanks filled with a solution of water and hydrochloric acid; this can be done in a pickling line, before the coils reach the tandem mill, or, more efficiently, the pickling line can be directly inserted between the welding machine and the 1st stand; additional loopers are required upstream of the stands to decouple the different phases giving maximum flexibility to such a plant, which can now reach 300 m length and accumulate 2000 m of strip in the loopers (see again Fig. 3; note that the figure is not to scale).

A few numbers taken from a typical plant can give an idea of the complexity of the cold rolling process and, as a consequence, of its automation system (Tab. 1): this real-time control system must deal with a highly-interconnected fast process and must guarantee accuracy, reliability and productivity by means of efficient generation of references for a large number of control loops able to run at cycle times of a few ms, connected to many actuators, sensors and supervision stations.

THE AUTOMATION SYSTEM

Fig. 4 illustrates the theoretical scheme of the automation systems, while Fig. 5 presents the automation layout for

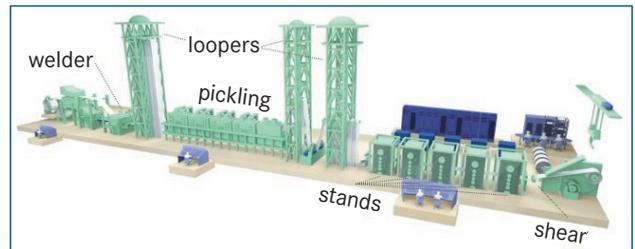


Fig. 3 – The continuous tandem mill coupled with pickling line (note that horizontal loopers are normally used)

Fig. 3 – Il laminatoio continuo a freddo accoppiato con decapaggio (decatreno); si noti che normalmente vengono installati accumulatori orizzontali

Entry thickness	5.5 ÷ 2 mm
Exit thickness	1.5 ÷ 0.14 mm
Thickness measure accuracy	± 0.01 %
Total thickness reduction	up to 90 %
Exit speed	20 m/s
Main motor power (5 stands)	15 ÷ 30 MW
Rolling forces	10,000 kN
Interstand tensions	100 ÷ 250 MPa
Thickness performances	± 1 ÷ 3 % exit thickness in 98 % of the strip body
Flatness performances	± 8 ÷ 12 I.U.
Production	1.2 millions tpy

Tab. 1 – Some typical data summarize the high-demanding capabilities requested from a modern cold rolling mill

Tab. 1 – Pochi tipici dati permettono di riassumere a colpo d'occhio i requisiti assai stringenti che un moderno laminatoio a freddo deve soddisfare

the continuous mill:

- Level 1: includes many regulators which control position or pressure of the hydraulic capsules, tension and thickness of the strip, speeds of the motors, and so on: inner and outer loops, concurrent loops, decoupling actions and on-line gain calibrations are often necessary; the level 1 also manages logic, sequences, hydraulics, communication with the field (sensors, actuators, electrical drives, operator desks, etc.). Data acquisition is used to investigate details in regulators.
- Level 2: the references to be sent to the regulators change depending on the different products to be rolled (production programs come from the production management department – level 3) and/or due to the intrinsic tempo-variance of the plant (e.g., work rolls

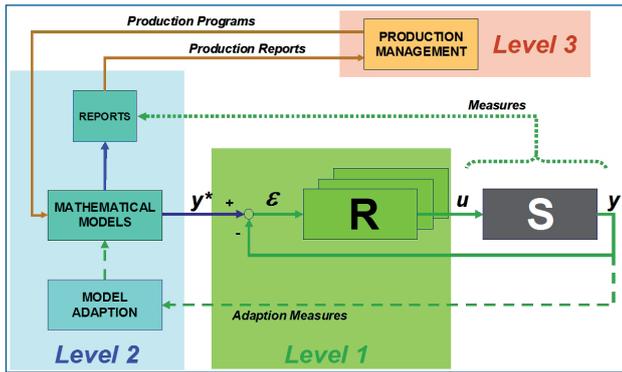


Fig. 4 – Functional structure of the automation system

Fig. 4 – Struttura funzionale del sistema di automazione

heat up and wear) so that they are recalculated by dedicated mathematical models for each new piece (consider many tens of pieces per day); measures are collected for autoadapting the models piece-by-piece and for certifying the quality of each coil produced.

The peculiar features of the continuous tandem mill automation system can be briefly described in the next paragraphs for adding more detailed information to the previous theoretical scheme.

SETUP CALCULATION AND LEVEL 2 BASIC FUNCTIONS

The rolling schedule to be actuated by level 1 is calculated by accurate mathematical models when the coil is welded, when it is at the pickling line or in the looper and before entering the tandem mill (final setup). Calculations dedicated to autoadapt the mathematical models for the next setup use actual plant measures and are carried out more than once while rolling the coil at the tandem mill in order to have more immediate impact on the next setup. A dedicated function (ARS – Aligned Rolling Strategy), side-by-side to autoadaption process, maintains satisfied the selected criterion (the rolling strategy) during rolling, by providing a redistribution of stand thickness reductions; e.g., ARS Load Balance guarantees the balancing of the motor powers in the stands of the tandem mill (see Fig. 6).

Finally, the process servers are dedicated to collect, manage and store all of the information related to each coil (primary data, rolling schedules, adaption calculations, applied sets, quality measures) and to production and operations. They also manage the connection to the level 3 system.

FLYING SETUP CHANGE

The world of the mathematical models and references actuation for rolling mills is quite wide and variegated, but what surely makes the difference in a continuous tandem

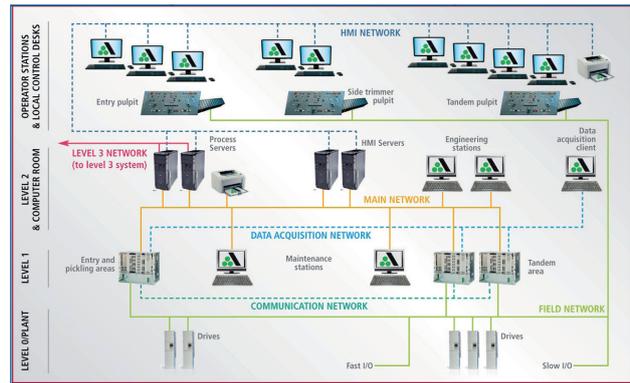


Fig. 5 – Automation layout for a continuous tandem mill coupled with pickling line

Fig. 5 – Configurazione del sistema di automazione di un decatreno

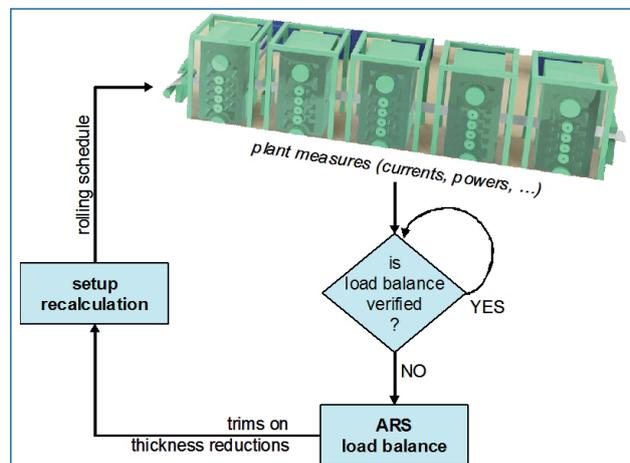


Fig. 6 – level 2 ARS load balance takes care that, during rolling, the stand powers are maintained in a balanced condition

Fig. 6 – La funzione di livello 2 ARS load balance fa in modo di mantenere le potenze delle gabbie in una situazione adeguatamente bilanciata durante la laminazione

mill is the flying setup change, that involves both modelling capabilities and real-time regulation and logic. The rolling schedule calculated for each coil to be rolled ensures the optimal references for that coil; but when the weld seam between two different coils passes through the stands, the mill operating point must move from the current state to the future state of the next product and the change has to be continuously managed by the automation system. Different intermediate sets (see Fig. 7), calculated by mathematical models and applied in the correct moments by regulators while weld seam moves along the mill, allow to maintain rolling stability (limiting the risk of strip breakage), to minimize the length of off-specification rolled strip by limiting the transition area and to maximize the production.

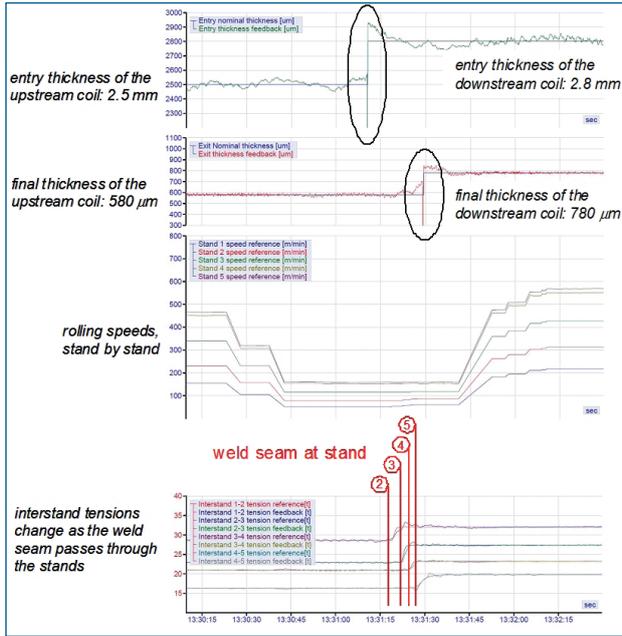


Fig. 7 - A weld is passing through the mill: the change of references is calculated and applied stand by stand (Continuous tandem mill - Italy)

Fig. 7 - Una saldatura sta attraversando il laminatoio: il cambio dei riferimenti è calcolato ed applicato di gabbia in gabbia (Laminatoio continuo a freddo - Italia)

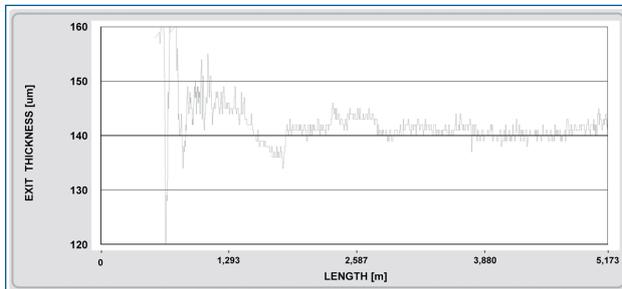


Fig. 8 - A minimum thickness of 140 µm has been reached during a test aimed at demonstrating the feasibility of so a thin thickness in a tandem mill (Continuous tandem mill - PRC)

Fig. 8 - Durante un test effettuato per dimostrare la capacità di laminare nastri estremamente sottili, si è raggiunto lo spessore di soli 140 µm (Laminatoio continuo a freddo - Repubblica Popolare Cinese)

THICKNESS AND TENSION CONTROL

The in-tolerance thickness of the final product is what immediately appears to the final customers and has a fundamental importance both on the strip quality and on the entire plant bounty (Fig. 8). The mathematical models (level 2) calculate the nominal stand reductions and interstand tensions in order to get the desired operating conditions in the absence of disturbances.

The technological controls (level 1) are designed to

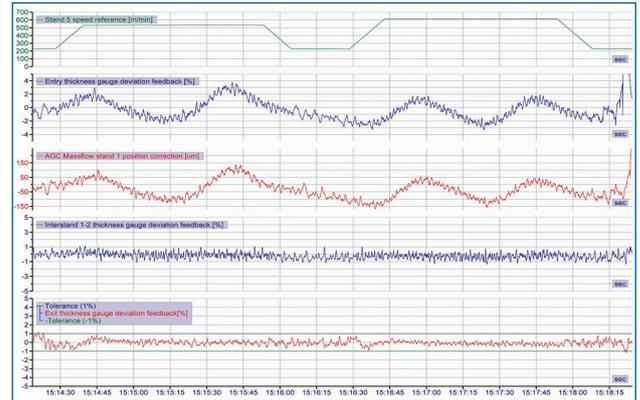


Fig. 9 - A coil with non-uniform thickness (e.g., due to skid marks at hot rolling) enters the 1st stand: AGC works very effectively so to bring the exit thickness within tolerances (Tandem Mill - Italy)

Fig. 9 - Un nastro con spessore non uniforme (p. es., dovuto a skid marks durante la laminazione a caldo) imbocca la 1^a gabbia: il controllo automatico di spessore (AGC) lavora con grande efficacia e mantiene in tolleranza lo spessore d'uscita (Laminatoio a freddo - Italia)

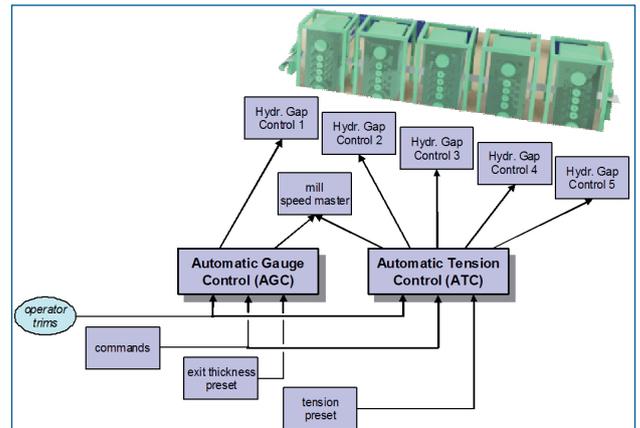


Fig. 10 - Thickness and tension control system at-a-glance

Fig. 10 - Un colpo d'occhio sul controllo di spessore e di tiro

minimise the variations in thickness and tensions which occur during rolling (see fig. 9): for example, thickness and hardness variations in the entry strip, thermal phenomena affecting the work rolls, roll wear, roll eccentricity and friction variations cause deviations from the guaranteed target thickness in the final product if not adequately controlled by the automation system (see the scheme in Fig. 10).

The *Automatic Gauge Control* (AGC - see Fig. 11) aims to

keep the strip exit thickness as near as possible to the target value; it is composed by three main subsystems, as hereby described.

- Entry AGC basically aims to keep constant and at the correct set the thickness of the strip exiting the 1st stand so that exit AGC, by receiving an incoming material at constant thickness, works at its best for guaranteeing the target exit thickness; it acts on the hydraulic gap control (HGC) of the stand 1. The mass flow control is based on mass flow constancy principle (the material entering the stand is equal to the one going out of the stand), as shown by the following expressions (h: thickness, v: speed):

$$h_{IN} \cdot v_{IN} = h_{OUT} \cdot v_{OUT} \quad (1)$$

Then mass flow control considers as error:

$$\varepsilon_{massflow} = \frac{v_{IN}}{v_{OUT}} - \frac{h_{OUT}^{target}}{h_{IN}} \quad (2)$$

Clearly, nullifying $\varepsilon_{massflow}$ means obtaining strip exiting the 1st stand at the desired thickness.

Mass flow control is the privileged choice because of its intrinsic and more robust characteristics: e.g., failures in laser speedometers can be successfully handled by using the encoders that are present both on entry bridle and in stand 1 (for example, the previous fig. 9 comes from a tandem mill without laser speedometers and shows that stand 1 exit thickness is maintained constant by the mass flow control in spite of entry thickness changes and rolling speed changes). The switching to the classical feedback-feedforward action is anyway possible for maintaining satisfying performances in case of heavy faults in other sensors (mainly, entry x-ray or speed encoders). The mass flow monitor aims to compensate for the mass flow estimation errors (measure errors, slipping, ...). Finally, note that mass flow control reduces the effects of roll eccentricity so dramatically to become a valid alternative to the eccentricity compensation in the 1st stand.

- AGC Monitor aims to bring the Exit AGC correction in range when it enters into a pre-saturation region; it recalibrates the Entry AGC thickness target, thus adjusting the material flow entering the mill according to the requirements of Exit AGC.
- Exit AGC closes the loop on the speeds of the last two stands, by performing the classical feedback mechanism.

The *Automatic Tension Control* (ATC) is aimed to maintain the interstand tensions at the preset values without affecting the AGC actions; different control configurations are used, depending on mill speed (normal run or low speed) and on product to be rolled (sheet or tin plate); fig. 12 shows the configuration in normal run mode.

Two different approaches have been implemented,

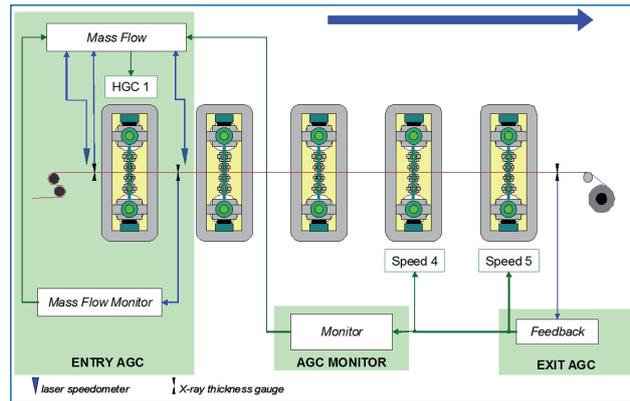


Fig. 11 - AGC control scheme

Fig. 11 - Lo schema di controllo dell'AGC

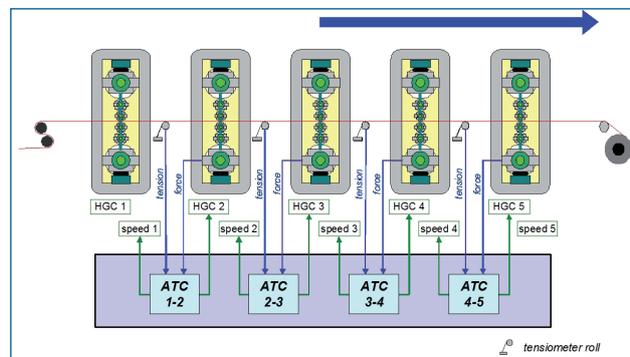


Fig. 12 - The scheme of ATC in normal run mode

Fig. 12 - Lo schema dell'ATC in modalità "normal run"

both of them valid and able to guarantee the required performances:

- Fuzzy ATC: the fuzzy principles allow the application of a natural human language to describe the problems and their fuzzy solutions; the way of working (as well as the system maintenance) is closer to the human reasoning, where good operating experience is more important than the theory of regulation. Starting from the experience achieved in the traditional approach, the traditional control schemes have been described in words, for adapting them to the fuzzy systems, and ATC has been further improved by taking into account the experience of the skilled operators (e.g., they tend to correct both on gap and on speed when rolling forces are high).
- Traditional ATC: the classical controls with PID regulators are used; the system is deeply based on the theory of regulation.

Fuzzy ATC is normally used because of its benefits in tuning and maintenance.

A number of rules describing how the algorithm has to consider the inputs for generating the outputs has been implemented by including both the control actions of a traditional ATC and the experience of skilled operators.

Fig. 13 – Fuzzy ATC in a tandem interstand

Fig. 13 – il fuzzy ATC nell'intergabbia di un laminatoio a freddo

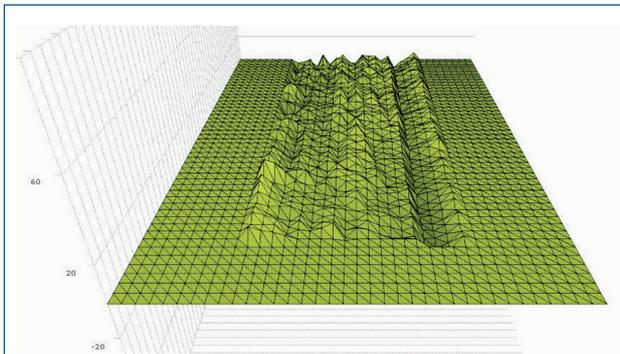
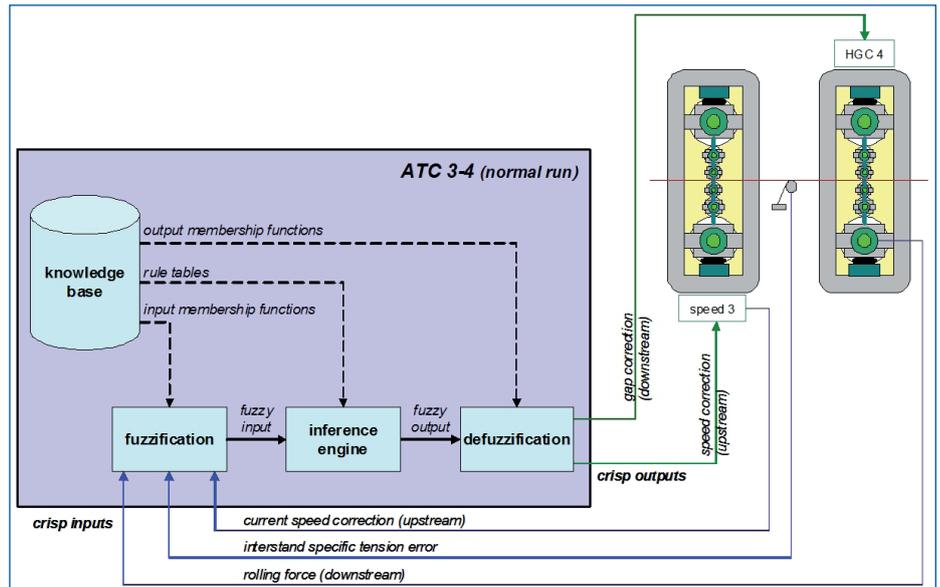


Fig. 14 – 3D representation of strip flatness error: note that every sample is in tolerance (± 12 I.U.) (Continuous tandem mill - Italy)

Fig. 14 – Rappresentazione tridimensionale dell'errore di planarità del nastro: si noti che tutti i campioni sono in tolleranza (± 12 I.U.) (Laminatoio continuo a freddo - Italia)

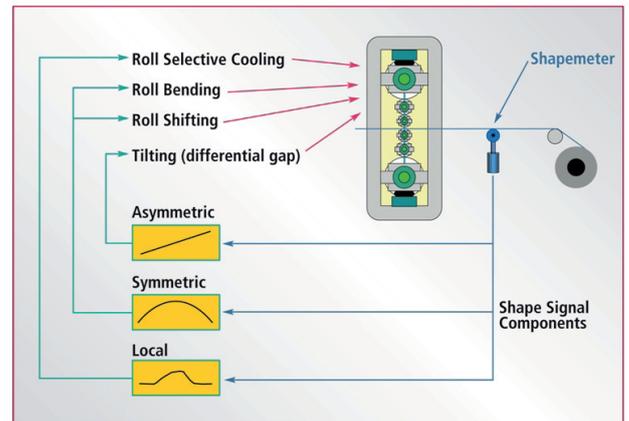


Fig. 15 – AFC: the 3 components of shape error are corrected separately

Fig. 15 – AFC: le 3 componenti dell'errore di planarità vengono corrette separatamente

The implemented fuzzy approach allows to well manage the intrinsic multiple-input multiple-output behaviour of ATC (MIMO control). Fig. 13, referring to the normal run configuration, allows to simply illustrate the way of working of the fuzzy ATC.

The inputs to the fuzzy ATC are tension error, measured force in the downstream stand (plant feedbacks) and current speed correction coming from speed master; these crisp inputs have to be transformed (fuzzification), by some “word descriptions”, so to be properly elaborated by the inference engine (based on Mamdani's direct method) for defining the fuzzy outputs (i.e., the control actions of ATC); the fuzzy outputs must, in turn, be re-transformed (defuzzification) into numerical values before being sent to the actuators. Tens of rules, stored in the knowledge base, allow the inference engine to generate an output; a rule is a description in the form “IF – THEN”, as in the next example:

IF tension error IS negative small AND force IS big
THEN gap correction IS zero AND speed correction IS positive small (3)

AUTOMATIC FLATNESS CONTROL

The strip flatness is the most important product characteristic, along with thickness, to which the steel market is extremely sensitive. A basic requirement is that the cold rolled strip must be flat and completely free of camber; flatness defects in the final product will occur if the residual stresses remaining after rolling exceed critical values. In this case, the strip will show flatness defects as wavy edges or centre buckles. Fig. 14 shows a snapshot of the 3D representation of flatness measured during rolling. Consider that the guaranteed tolerances range around 10 I.U. (International Units) and this means to detect and control a delta length between the wavy and the tight

fibres of 1 mm only in a wave 10 meters long.

Strip flatness is measured with a shapemeter: a segmented roll located at the 5th stand exit which measures, rotor by rotor, the vertical forces to which the strip is subjected during rolling, across the width of the strip; it is then mathematically possible to obtain the longitudinal tensions from the forces and, from them, the flatness index of the strip.

The flatness control processes rough measurements coming from the shapemeter in order to extract the three components of the error that the available actuators

can most efficiently correct (see Fig. 15); bending and intermediate shifting quickly and accurately compensates for symmetrical defects, while tilting acts on the asymmetrical defects in the strip. Localized defects, usually a result of thermal phenomena, can be efficiently corrected by selective cooling sprays: they have a slow dynamic, but can act on a precise area of the strip.

A Feedforward Force Compensation function (FFC) calculates a further contribution of bending, taking into account that the force can change during rolling, e.g. due to corrections from AGC, or from ATC.

Il sistema di automazione Nidec ASI per un decatreno

Parole chiave: Laminazione - Controllo Processi - Siderurgia - Acciaio

La laminazione a freddo è uno dei settori principali della laminazione dei prodotti piani e il tandem continuo è certamente uno degli impianti più completi e significativi nell'ampio panorama della siderurgia. In un processo di tale sorta, che deve soddisfare requisiti di produttività e qualità finale del rotolo sempre più stringenti, un sistema di automazione altamente performante ed affidabile è di conseguenza indispensabile per ottenere il massimo dalle apparecchiature meccaniche ed idrauliche.

Questo articolo illustra sia l'impianto che il sistema di automazione, focalizzandosi sugli aspetti più significativi dell'automazione sviluppata dalla società, dai modelli matematici agli algoritmi di regolazione fuzzy, ma senza trascurare l'architettura globale del sistema.

La storia della moderna laminazione a freddo cominciò molti decenni fa; i sistemi di automazione iniziarono gradualmente a giocare il loro ruolo accrescendo sempre più la loro importanza fino a diventare una parte indispensabile del processo di laminazione.

Una breve descrizione del laminatoio continuo a freddo con decapaggio in linea (decatreno), uno degli impianti più complessi dell'intero settore siderurgico, permette di dare uno sguardo ai requisiti coi quali deve essere prodotto oggi un rotolo di alta qualità. Un'idea del sistema di automazione necessario per soddisfare requisiti così stringenti in un decatreno è data dalla successiva presentazione del layout di automazione.

La seconda parte dell'articolo illustra i vari livelli di automazione e fornisce alcuni dettagli relativi ai principali controlli tecnologici e modelli matematici, citando naturalmente gli ultimi miglioramenti introdotti: dai modelli matematici autoadattivi con cambio di set al volo al bilanciamento in linea dei carichi delle gabbie, dai fuzzy control applicati al controllo di tiro intergabbia ai controlli di spessore e di planarità.