Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 00 (2019) 000–000

www.elsevier.com/locate/procedia

31st CIRP Design Conference 2021 (CIRP Design 2021)

An Artificial Intelligence approach for the in-line evaluation of steels mechanical properties in rolling

T. Magro[a,]*, A. Ghiotti[a], S. Bruschi[a], A. Ferraiuolo[b]

[a]*Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131, Padova, Italy*
[b]*Marcegaglia S.p.a., Via Baiona 141, 48123, Ravenna, Italy*

* Corresponding author. Tel.: +39-049-827-6819. *E-mail address:* tommaso.magro.1@phd.unipd.it

Abstract

The large demand of high-performance steels to improve the safety and energetic performances in automotive is driving the increasing need of higher uniformity of mechanical properties of rolled products, both within a single coil and in large batch productions of multiple coils. To achieve these targets, we are witnessing an evolution of rolling towards the introduction of sensors and Artificial Intelligence (AI) algorithms to allow the real-time monitoring of both the strip tensile properties and the evolution of microstructure during the annealing process.
The work described in the paper is part of a research work that is aimed at developing an AI framework that could allow the full real-time control of the entire mill rolling plant thanks to (i) innovative sensors applied at different steps of the coil processing, (ii) mixed analytical and numerical algorithms for the data computation and analyses, and (iii) IT infrastructure to collect and elaborate the data. The focus of the paper is on the tension-levelling operation which is one of the first that is performed in the rolling mill and can have a relevant influence on the strip mechanical characteristics. To reach this aim, a predictive model applicable to the tension-levelling process was developed, as this process is used to minimize flatness imperfections and residual stresses by means of plastic deformation. During the process, the material is subjected to cyclic tension-compression stresses, obtained with repeated and alternate bends under superposed tension. Consequently, the desired product standards, in terms of thickness and flatness, are achieved, while the mechanism of deformation changes the final mechanical properties of the material, increasing the yield strength and decreasing the maximum elongation. Finally, the predictive model is used to predict the coil mechanical characteristics, by using the data sampled from the sensors placed inside the tension-levelling machine.

Keywords: Sheet metal forming; rolling; tension-levelling; artificial intelligence.

1. Introduction

The growing demand for steel market products characterized by high quality, low steel prices and the need to comply with international environmental regulations on greenhouse gas emissions have motivated steel industry to move towards a deep revision of the logic of production. Accordingly, the common demand for homogeneous and constant material properties, processes efficiency, reduction waste of material and reduced energy consumption is now added by the requirement of real-time control of all these parameters in the event of non-compliance of the product mechanical properties for the prompt adjustment of the full process chain.

It is nowadays well recognized that uniform microstructure properties of a rolling product under tensile stress conditions can be obtained only through a tight control of the annealing furnace temperature, which depends on the material emissivity and on the strip surface conditions (such as roughness and cleanliness). Shape defects in strip products may be caused by various factors, such as: differential reductions applied across the material width at rolling mills, non-uniform distribution of the internal residual stresses along the thickness direction, non-uniform mechanical properties due to uncontrolled microstructural transformations, and improper staking during transportation [1].

In Roberts [2], the main influencing factors that lead to defects in cold-rolled strip are described as well as the main

Nomenclature

R_i	radius of the i-th roller;
R_{i+1}	real radius of the roller following the i-th one;
t	sheet thickness;
w	sheet width;
E	Young's modulus;
α	geometric contact angle of the sheet with the roller;
$F_{left,i}$	force calculated in input to the i-th roller;
$F_{right,i}$	force calculated at the output of the i-th roller;
μ	friction coefficient;
$F_{normal,i}$	normal force calculated at the i-th roller;
$F_{friction,i}$	friction force calculated at the i-th roller;
$\varepsilon_{st,i}$	axial deformation at the i-th roller due to the stretch;
$\varepsilon_{st,tot}$	total axial deformation due to the traction generated by the bridles;
y	distance of a generic fiber from the centreline of the sheet;
e	displacement of the neutral axis from the sheet metal centreline;
$\varepsilon_{ben,i}$	axial deformation at the i-th roller due to the bending moment;
ε_{tot}	total axial deformation equal to the sum of the contributions related to the bending moment and the traction;
v_1	tangential speed in input;
v_2	tangential speed at the exit;
K	coefficient of resistance of the material;
n	material hardening coefficient;
m	strain rate sensitivity coefficient;
φ	sliding coefficient between sheet and roller;
E_{load}	energy related to the input and output force;
$E_{friction}$	energy linked to the force of friction;
$E_{deformation}$	energy related to sheet metal deformation;

shape defects that affect the quality of the products. Concerning the strip flatness, the most frequent defects are the coil set, generated by the re-coiling process, and the crossbow, created by an uneven cooling of the rolling stock across the strip width or slitting. Edge wave, centre buckle, camber and twist are other typical defects that degrade the sheet or make it unusable.

Several processes are commonly used to remove or reduce these defects, including (i) pure stretch levelling, (ii) multi-roller levelling (i.e. roller levelling), and (iii) stretch-bend levelling (i.e. tension-levelling) [3,4], exploiting the stress generated by stretching and bending. In the former, high brindle drum tensions are required to plasticize the material, overcoming the yield stress point and flattening the material. In multi-roller levelling, repeated bending and counter bending deform the strip by means of multiple rollers arranged alternately, which increase the curvature radius decreasing the rollers gap while the strip moves along the process to obtain higher flatness [5]. In the latter, a combination of longitudinal tension and bending is applied to the metal sheet, reaching stress which can be equal up to the 70% of the initial yield stress [6]. To reduce the magnitude of the front and back tension required in the tension-levelling process, small rollers' radii are commonly used, since material yielding is due mainly to the bending contribution rather than the axial tension [7].

Nowadays, most of the process parameters among those described above (i.e. roller-intermesh, tensile load, brindle-rollers velocities, roller-pitches and roller-radii, etc.) are still determined by trial-and-error approaches [8] and often do not allow a strict respect of the tolerances with flatness errors up to 20 mm [9], obviously causing low quality, low efficiency and high waste of material. Furthermore, also with regard to process repeatability, industrial guidelines do not guarantee accurate process control: as an example, it can be mentioned that the suggested strip elongation may range from 0.3% up to 5% [10, 11], strongly limiting a unique approach according to the material and thickness and introducing random variables that influence the process setup.

From a review of the scientific literature, several contributions were found, in which empirical and numerical approaches have been developed about the selection of the optimal process parameters for sheet metal levelling. Pioneering experimental studies were carried out by Sachs and Klinger [12] and Tanaka *et al.*[13], investigating the curling of metal sheets in asymmetric rolling and concluding that the sheet defect was correlated to the frictional forces generated during the process. Following these studies, different analytical models were developed: for example, the Misaka and Masui [14] model allows calculating quantitatively the sheet curl depending on the elongation, while with the Pospiech [15] model, different process parameters, such as the lubrication, the strip thickness and the rollers' roughness were taken into account. The investigations of Kinnavy [16] made it possible to create many analytical models today-used. The model describes the neutral layer (NL) position as function of the strip tension under superposed bending by the forward and backward loads, however it does not consider the optimization of the process parameters to obtain certain stress or geometrical conditions. It is with the Doege *et al.* [17] analytical model that it is possible to calculate the optimal rollers position considering the residual stresses along the sheet thickness, however the first concept of optimizing the roller position came with Liu *et al.* [18], that analysed the curvature of the strip after the levelling without taking into account the residual stresses. With respect to the tension-levelling process, very few studies can be cited from literature. Morris *et al.* [6] studied the residual stresses and the Bauschinger effect, comparing analytical and FE modelling. Yoshida and Urabe [8] developed a FE model by using a sophisticated constitutive model based on cycling plasticity and it was found that the roller intermesh has little influence on the product properties, while Huh [7] by using numerical analyses showed the correlation between the strip elongation and the number of rollers and forward/backward tensions.

The work presented in this paper is part of a visionary industrial project based on the most advanced manufacturing technologies, mostly aligned with the Industry 4.0 pillars, which have been implemented for the first time in an industrial plant to have the full control of a cold rolling mill. By satisfying the growing demand from OEMs for improved uniformity of strip tensile properties, the project, named *Master Model*, aims at allowing metallurgists to have the real-time knowledge of the main physical characteristics of the raw material – namely the hot rolled coil – and the evolution of the strip mechanical properties during the annealing process. The present paper describes the part of the research work that is devoted to the development of an AI framework that could allow the quantitative design of the metallurgical characteristics of new steels as well as the full real-time point-to-point control of the product properties along the entire mill rolling plant. To this aim are adopted (i) innovative sensors applied at different steps of the coil processing to collect process data, (ii) mixed analytical and numerical algorithms for the data computation and analyses, and (iii) IT infrastructure to collect and elaborate the data.

2. Case study

The *Master Model* project was implemented by Marcegaglia Group at the rolling plant located in Ravenna (Italy) with an approach which follows the Industry 4.0 concepts in order to produce steel products with exceptional uniformity of tensile-structure properties, increasing the productivity and optimizing the energy efficiency of the whole manufacturing process. The case study hereby presented regards the tension leveller unit that is located at the beginning of the process chain.

2.1. Tension leveller unit

Fig. 1 represents the configuration of the tension leveller unit, in which the tensile load is applied to the strip by two brindle-rollers, whose speed is made to vary in order to maintain the constant elongation of the sheet, before and after the tension leveller machine. The so-called process unit is made of 2 brindles placed at the entrance and at the exit of the tension-levelling process and 5 working rollers that are grouped into: (i) two couples of small-radius rollers, named work rollers, followed by large-radius rollers adjustable and un-driven, named guide rollers, and (ii) a couple of guide rollers plus a single work roller. The first group imposes the alternate bending to the strip, while the latter is positioned at the exit of the process unit for the elimination of the crossbow defect.

Tension-levelling is particularly sensitive to several parameters and, for example, small variations of the sheet geometrical parameters, such as the thickness or the width, may cause significant deviations in the final shape of the coil. So, having constant process parameters, the material supply conditions may also determine different properties of the final product in terms of strip geometry, mechanical properties, residual stresses, etc. Due to that, the only parameter that is generally made to vary in the industrial plant is the load generated by the brindles, while the intermesh between the work rollers and their radius are usually kept constant. The deformation imposed to the strip can be divided into three stages according to the loads that are applied, having respectively:

- deformation induced by the tension generated by the brindle rollers;
- elastic bending deformation and elastic-plastic deformation generated by the work rollers;
- elastic recovery during the unloading.

Because of the superposed tension that can expand the tensile zone and minimize the compression zone of the strip, according to Marciniak [19], the strip neutral layer moves towards the centre of curvature and changes its position along the process due to the alternate direction of the bending moment. Moreover, the shape of the strip significantly varies from the theoretical one when using high strength materials, changing the position of the contact points between rolls and the strip from the theoretical tangential points.

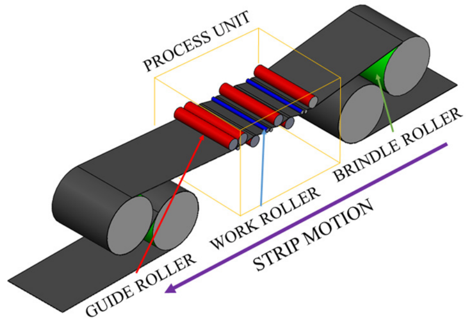


Fig. 1. Tension-levelling process configuration.

The current working conditions of the tension leveller unit may generate different mechanical properties along the coil, since constant process parameters are not used which cause the material to undergo different deformation histories and different hardening. This variability is partially corrected by the subsequent processes, but a slight variation spreads to the final component. Being a continuous process, it is impossible to carry out samples, except by stopping the machine and cutting a piece of coil. Samples are therefore used in random mode in the first and last section of the coil, in order to have a general idea of the mechanical characteristics. This makes the result of the process very unstable, and based above all on the skill of the operator in choosing optimal process parameters, without then changing them.

2.2. Real time control of the tension leveller unit

The diagram reported in Fig. 2 shows the link between the tension-levelling process and the analytical model developed within the project. Specifically, the input data for the process parameters are represented by the sheet parameters, i.e. material, geometry and supplier. In particular are note the characteristics of the material in terms of Young's modulus E, coefficient of resistance of the material K, hardening coefficient n, strain rate sensitivity coefficient m, the geometric characteristics, therefore thickness and width, and the supplier. In addition, nominal values for the yield stress can be obtained by tensile tests carried out on samples manufactured by the coils. Knowing these data, it is possible to set the tension leveller unit with first attempt process parameters based on the knowledge of the operators and/or the company experience.

Since the parts of the tension leveller machine are totally sensorized, a considerable amount of data is available for the analytical model, for example the speeds of each roller, the forces generated on the machine constraints, the positions of the rollers, the brindles loads, the elongation, etc. The idea was to exploit this amount of input data relating to process data, choosing the most significant ones as regards the mechanical characteristics at the output of the tension leveller unit. From the analysis of the literature and the experience of the line operators, it was decided to neglect the intermesh of the rollers and their positions, and to consider (i) the stretch forces generated by the inlet and output brindles (T_1 and T_2), (ii) the elongation imposed by the machine on the coil ($A_{\%}$), and (iii) the input and output speeds (v_1 and v_2), in order to make it possible changes to these process parameters without having to stop the machine.

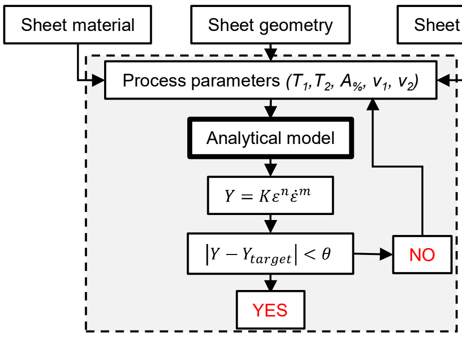


Fig. 2. Real-time scheme of the tension-leveller unit.

The process data sampled by the sensors embedded in the tension leveller unit allow feeding the analytical model, framed with the black colour. The analytical model allows having as output data the mechanical characteristic of the coil, specifically the yield stress. Comparing this value with a target value (known from the company database and obtained with tensile tests), it is possible to either modify the process parameters or confirm the output characteristics of the coil. This method also guarantees to have continuous data, and therefore to be able to recognize the mechanical characteristic of the sheet along the length of the coil, significantly reducing any waste of material.

2.3. Data sampling from the tension leveller unit

All the data sampled during the process with a frequency of 10 Hz were analysed both in the time and space domain, after having filtered them in order to reduce the number of data to be processed and have a frequency of 1 Hz. This was done to see in the first case any speed variations, while in the second case to have the tracking of the process parameters sampled for each meter. The preliminary analysis of the production in the reference plant showed that coils, having the same nominal material and geometrical characteristics, but provided by different suppliers were significantly different in terms of mechanical properties and required different process parameters of the tension leveller unit, in particular for the elongation imposed and the speed of the brindles. Therefore, it was decided to analyse each individual coil family based on historical data, implementing the model with calibration factors obtained by comparing the target value from the tensile tests with the one measured by the analytical model. Once the model was calibrated, the same was implemented within the company software, creating a new string of data as if they were derived from a sensor.

Once validated, the model has been executed in the tracking software implemented in the rolling mill and this allowed the operator to know in real-time the mechanical characteristics of the processed coils and to adjust the process parameters accordingly. The final step will be to make this process control fully automated, in order to reduce as much as possible the human and random variables that influence the final result, possibly having the opportunity to correct the imperfections with subsequent processes, knowing exactly the position of the areas of non-compliance with the starting target.

3. Model description

3.1. Model outline

The flow chart reported in Fig. 3 describes the analytical procedure to calculate the yield stress of the coil from the process and material parameters. The model is based on three iteration procedures (represented inside the rectangles with a grey background), (i) evaluation of the load for each roller, (ii) evaluation of the bending strain and (iii) minimization of the total energy during the process.

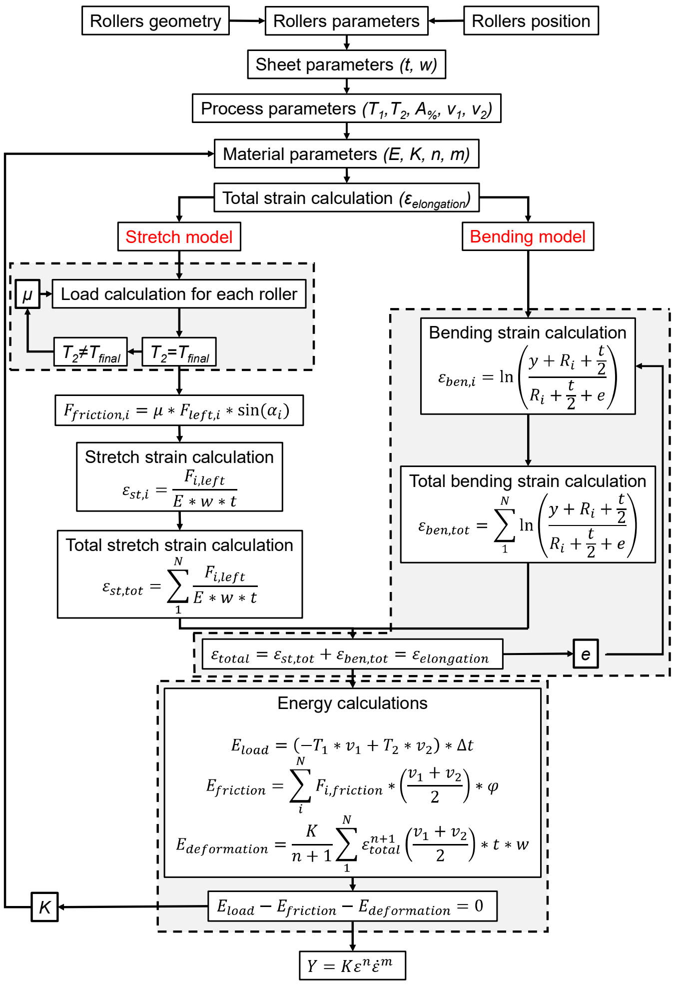


Fig. 3. Model flow chart.

The three variables of the iterative procedures framed with the black colour are (i) the friction coefficient (μ), (ii) the shift of the neutral axis (e) and (iii) the strength coefficient (K). The total deformation is calculated by superposing the effects deriving from the axial deformation, calculated by means of the so-called *stretch* model, and the bending deformation, calculated by means of the *bending* model. Once the strip elongation is calculated, it is possible to compare the real elongation with the analytical one, and modify, through the two iterative procedures present, the value of the deformation.

Having known the subdivision of the deformation, by a balance of energy it is possible to calculate the value of the material parameter *K*, while the hardening coefficient *n* and the strain rate sensitivity coefficient *m*, which are used to calculate the actual yield value of the material, are considered constant and equal to the nominal values obtained with the tensile tests.

3.2. Model analytics

Regarding the iterative procedures shown in Fig. 3, the iterative variables present in the equations and the results obtained are described below. The first iterative procedure is that for the calculation of the friction coefficient. The coefficient of friction is found from the equilibrium of the force at the exit of the last roller and the force measured at the exit bridle, according to Eq. 1-4 proposed afterwards.

$$F_{left,i} = F_{right,i-1} \quad \text{eq. 1}$$

$$F_{friction,i} = F_{left,i} * sen(\alpha_i) * \mu \quad \text{eq. 2}$$

$$F_{normal,i} = F_{left,i} * sen(\alpha_i) \quad \text{eq. 3}$$

$$F_{right,i} = \frac{F_{left,i} * \cos(\alpha_i) + F_{normal,i} * \operatorname{sen}(\alpha_i)}{\cos(\alpha_{i+1})} \quad \text{eq. 4}$$

The second iterative step concerns the calculation of the total deformation that is obtained as sum of two contributions: the first linked to the tension generated only by external forces, and the second due to the bending moment. The iterative procedure allows calculating the displacement of the neutral axis to have the total axial deformation equal to the elongation imposed by the machine (Eq. 6), thus having as a variable the displacement of the neutral axis, indicated with *e* in Eq. 5:

$$\varepsilon_{ben,tot} = \sum_{i=1}^{N} \ln\left(\frac{y + R_i + \frac{t}{2}}{R_i + \frac{t}{2} + e}\right) \quad \text{eq. 5}$$

$$\varepsilon_{total} = \varepsilon_{st,tot} + \varepsilon_{ben,tot} = \varepsilon_{elongation} \quad \text{eq. 6}$$

The last iterative routine regards the total energy spent by the system to carry out the process and is used to determine the resistance coefficient of the material *K* (Eq. 10). The energy balance is between the external forces impressed by the bridle and internal energy spent to overcome the friction between the coil and the rollers and the material deformation, according to Eq. 7-9. It is made under the assumption that the hardening coefficient *n* and the strain rate sensitivity coefficient *m* of the material are known from the tensile tests carried out offline.

$$E_{load} = (-T_1 * v_1 + T_2 * v_2) * \Delta t \quad \text{eq. 7}$$

$$E_{friction} = \sum_{i}^{N} F_{friction,i} * \left(\frac{v_1 + v_2}{2}\right) * \varphi \quad \text{eq. 8}$$

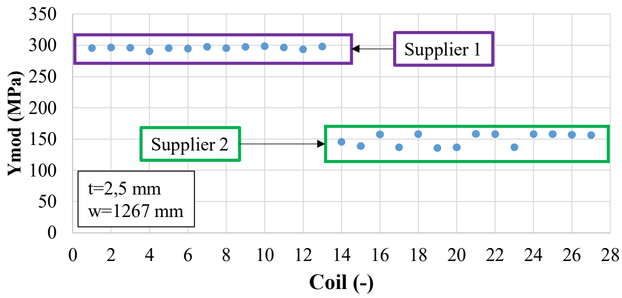
$$E_{deformation} = \frac{K}{n+1} \sum_{1}^{N} \varepsilon_{total}^{n+1} \left(\frac{v_1 + v_2}{2}\right) * t * w \quad \text{eq. 9}$$

$$E_{load} - E_{friction} - E_{deformation} = 0 \quad \text{eq. 10}$$

4. Results

4.1. Model calibration

Fig. 4 shows two examples of model calibration where the same geometric parameters are considered but different suppliers. The average values relating to the yield stress of two different SAE1006 steel coils obtained before the model calibration procedure, considering a thickness of 2.5 mm and a width of 1267 mm for the first case and a thickness of 3.0 mm and a width of 1265 mm for the second case, are different. Furthermore, it is possible to note in both cases how the output of the model with the same geometric and supplier conditions is constant.



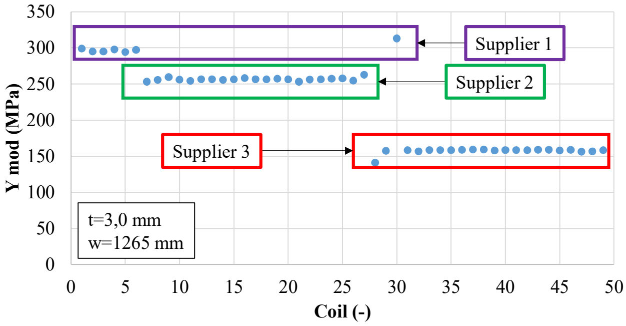


Fig. 4. Yield stress calculated from the analytical model for different mechanical characteristics or different suppliers.

The calibration procedure consists in comparing a target value obtained from tensile tests for the same coil family (same material, same geometric characteristics, same supplier) with the value obtained from the model, and, through a corrective coefficient a_{ijk} (Eq.11), allows to align the values obtained from the model with those obtained from tensile tests carried out offline. In particular, the coefficient takes into account (i) different geometric parameters, (j) different materials and (k) different suppliers, guaranteeing the possibility of identifying all the possible combinations that are processed in the tension leveller unit.

$$Y = a_{ij} * Y_{target} \quad \text{eq. 11}$$

4.2. Tension leveller process monitoring

Once the model is calibrated for each type of incoming sheet, it can be used online. Specifically, two data strings are created, one relating to the point value of the yield stress for each meter of the sheet, as the Fig. 5a, and an average, based on the total length of the coil. In the graphs, the yield stress values are normalized using the company target value, following the criteria of type of material, supplier, and geometry. The first value (Fig. 5a) allows to improve and/or vary the process parameters and to recognize any non-compliance areas, reducing the risk of incorrect evaluation of the mechanical characteristics before sale, while the second data relating to an average value allows to feed the company database and the first attempt process parameters. Fig. 5a reports the results in the domain of the space of a SAE1006 coil, having a thickness of

3,0 mm and a width of 1265 mm, in which in the first part of the graph it is possible to notice the high variability of the mechanical characteristics of the coil calculated with the analytical model, while in the second part it is possible to notice the significant improvement in the quality of the output data.

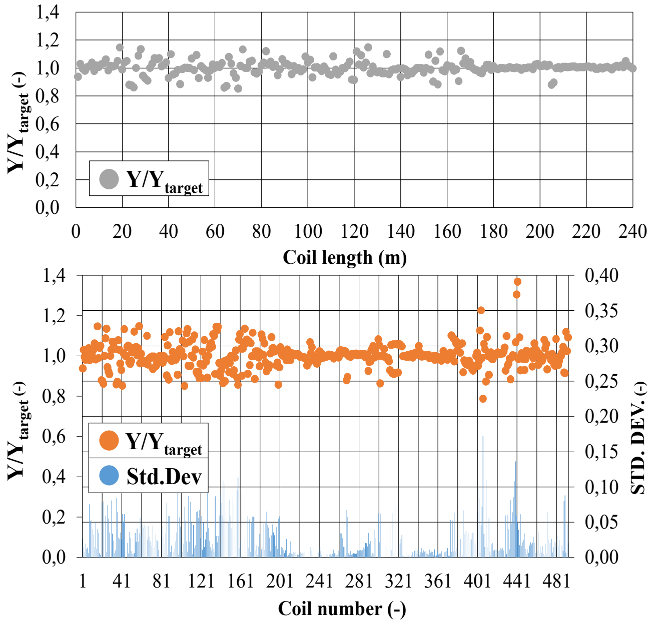


Fig. 5. a) Yield stress calculated from the analytical model normalized with the target value through the length of the coil, b) Yield stress calculated from the analytical model normalized with the target value through the number of the coil.

Fig. 5b shows the average yield strength data of coils with different characteristics, reporting the standard deviation with the bars in the bottom part of the graph. It has been estimated, through the use of the company database, that with the use of this procedure it is possible to obtain 81.8% of the mechanical properties of the coils in compliance with the yield strength using 1σ for the standard deviation, 97.4% using 2σ and 99.8% using 3σ.

5. Conclusions

The present paper describes part of a research work that is aimed at developing an AI framework that could allow the full real-time control of the entire mill rolling plant. In particular, the influence of the tension-levelling process in the mechanical characteristics of the coil was investigated, following an analytical approach to predict the yield stress after the tension-levelling process. The model allows to forecast the optimal process parameters to obtain homogeneous mechanical properties depending on the geometric parameters of the coil, namely the thickness, the width, the material constitutive parameters, such as the value of the hardening and strain rate sensitivity coefficients, and the supplier of the coil. In addition, the model permits calculating the yield stress of the metal sheet during the whole process, subdividing the sheet meter by meter and investigating the influence of each roller.

The algorithm has been implemented in the tracking software of Marcegaglia plant, and this allows the operator to immediately have the knowledge of the mechanical characteristics of the material being produced, possibly modifying the process parameters of the tension-leveller unit. The input data are the geometry of the sheet, the supplier and the material, while the output data are the average yield stress of the coil and the yield stress value for each part of the coil. The knowledge of the mechanical characteristics combined with the possibility for the company to have a complete tracking of the coil within any process, guarantees the theoretical possibility of correction up to the end of the line, standardizing, even though subsequent processes, the mechanical characteristics of the coils.

Future activities will be to make this process control fully automated, in order to reduce the waste of material, increasing the quality, the homogeneity of the product and the overall efficiency of the plant.

Acknowledgments

The authors wish to thank the company Marcegaglia S.p.A (Italy), for the support provided in the definition of the industrial case and the data made available.

References

1. Tomita S, Fujita Y. Recent trend and problems of straightening technologies of thick plates. *J. Jpn. Soc. Technol. Plast.* 1999; **40**:408-11
2. Roberts WL. *Cold rolling of steel.* Marcel Dekker, New York, 1978
3. Park KC, Hwang SM. Development of a finite element analysis program for roller levelling and application for removing blanking bow defects of thin steel sheet. *ISIJ Int.* 2002; **42**:990-99
4. Sheppard T, Roberts JM. Shape control and correction in strip and sheet. *Int. Met. Reviews*. 1973; **18**:1-18
5. Lee JB, Kang SS. Numerical modelling of roller leveller for thick plate levelling. Int. J. Precis. Eng. Manuf. 2018; **19**:425-30
6. Morris JW, Hardy SJ, Lees AW, Thomas JT. Formation of residual stresses owing to tension levelling of cold rolled strip. *Ironmaking & Steelmaking.* 2001; **28**:44-52
7. Huh H, Lee HW, Park SR, Kim GY, Nam SH. The parametric process design of tension levelling with an elasto-plastic finite element method. *J. Mater. Proc. Tech.* 2001; **113**:714-19
8. Yoshida F, Urabe M. Computer-aided process design for the tension levelling of metallic strips. *J. Mater. Proc. Tech.* 1999; **89**:218-223
9. Morris JW, Hardy SJ, Thomas JT. Some fundamental considerations for the control of residual flatness in tension levelling. *J. Mater. Proc. Tech.* 2002; **12**:385-96
10. Zhou C, Jiang Z, Wang G, Xie D, Zhang Y. Analysis of tension and deformation curvature in strip tension levelling. *Adv. Mater. Research.* 2010; **97-101**:71-74
11. Huh H, Heo JH, Lee HW. Optimization of a roller levelling process for Al7001T9 pipes with finite element analysis and Taguchi model. *Int. J. Mach. Tool. Manuf.* 2003; **43**:345-50
12. Sachs G, Klinger L. The flow of metals through tools of circular contour. *J. Appl. Mech.* 1947; **14**:88-98
13. Tanaka E, Tsunokawa K, Fukuda T. Curling and bowing of rolled strips. *Trans. Jpn. Inst. Met.* 1963; **4**:124-33
14. Misaka Y, Masui T. Shape correction of steel ship by tension leveller. *Iron Steel Inst. Jpn.* 1971; **18**:475-84
15. Pospiech J. A note on the influence of some factors affecting curvature in the flat rolling of strip. *J. Mech. Work. Tech.* 1987; **15**:69-80
16. Kinnavy MG. Methods of permanently elongating strip. United States Patent Office 3552175
17. Doege E, Menz R, Huinink S. Analysis of the levelling process based upon an analytic forming model. *CIRP Annals – Manufacturing Technology.* 2002; **51**:191-94
18. Liu Z, Luo Y, Wang Y, Liao TW. A new curvature analytical method in plate levelling process. *ISIJ Int.* 2018; **58**:1094-101
19. Hu J, Marciniak Z, Duncan J. Mechanism of sheet metal forming. Elsevier, 2002