Article citation info:
Papini S, Valigi CM. Analysis of chattering phenomenon in industrial S6-high rolling mill. Part II: experimental study. Diagnostyka 2016;17(4):27:-32.

DIAGNOSTYKA 2016, Vol. 17, No. 4

ISSN 1641-6414
e-ISSN 2449-5220

ANALYSIS OF CHATTERING PHENOMENON IN INDUSTRIAL S6-HIGH ROLLING MILL. PART II: EXPERIMENTAL STUDY

Susanna PAPINI *, Maria Cristina VALIGI **
* University of Florence, Department of Industrial Engineering, Italy
Strada Santa Marta 3, 50139, Florence, Italy, e-mail: susanna.papini@unifi.it
**University of Perugia, Department of Engineering
Via G. Duranti,1 06125 Perugia, Italy, e-mail: mariacristina.valigi@unipg.it

Abstract

The paper represents an extension of a previous work where the problem of chatter in a rolling mill producing advanced high-strength steels (AHSS) was investigated by a combination of a linear lumped parameter model and the slab analysis. In this paper the authors show the detailed experimental study of the problem with a complete description of all the phases related to the vibrational investigation that lead to the solution of the problem. Furthermore, a different model based on the Orowan's method together with a non-linear model of the rolling mill is presented and simulations are performed.

Key words: chatter, vibration analysis, AHSS, Orowan's method, rolling mill

INTRODUCTION

Chatter vibrations represent one of the main problems of rolling mills. These vibrations are the result of the interaction between rolling mill structure and rolling-process [5-10].

This paper represents an improvement of the paper [19], where further vibrational analyses are performed with the aim to detect and avoid the insurgence of chatter. Its manifestation is recognisable from the classical regular, parallel markings across the width of the metal strips, called "chatter marks" [11], [13-17], [22-24]. The studied S6-high rolling mill produces AHSS and it is suitable to realise high reductions of strips (up to 1:12) in one pass [8]. In a traditional production cycle, the hot rolled strip is annealed and pickled before to be rolled and finally again annealed and pickled [25]. Therefore, each of these phases involves the movement of material with the use of overhead cranes and special trolleys. Instead, the production system investigated in this paper is able to produce roll steel strips coming directly from hot rolling mill trains: the strip is ready for further reductions in thickness or for the market. Since the interactions between the process and the structure is nonlinear, a more complex model is established with respect to the previous paper [19]: the deformation of the metal strip roll bite is considered inhomogeneous and treated according to the Orowan's method [12][24].

A non-linear different lumped parameters model is proposed and simulations are performed. In addition, a detailed vibration analysis is performed.

1. CHATTER MARKS AND VIBRATION ANALYSIS

As it is showed in [19] the studied S6-High rolling mill consists of two subsequent stands each of them made up of six rolls and having four cassettes with four side support rolls (SSRs) arranged inside (Fig. 1).

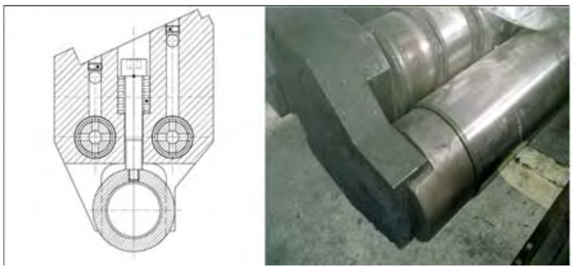

Fig. 1. Sketch and transversal section of side support roll [14]

The studied plant, suffered chatter vibrations and at the moment of replacement of the SSR cassettes, an abnormal and unexpected deterioration of the SSR cylinder appeared, together with chatter marks on the metal strip. The chatter marks followed a periodic trend during rolling campaigns, with the SSR replacement. This problem has led to replace the rolls in advance (after about 150 km) with respect to the time period suggested by the manufacturer (after 500 km).

The fig. 2 shows the marks on changed work rolls. The chatter marks on the metal strip had a frequency of 130 Hz (2 marks per cm at 40 m/min rolling speed). In this first section of the paper a

detailed analysis of the vibration is showed according to standard ISO normative [3] and involving the following systems:
- rolls grinding machine;
- gear-box system;
- the second stand.

Fig. 2. Chatter marks on the roll

1.1. Rolls grinding machine

As an inadequate grinding of the rolls involved in the process can be the cause of strip defects, roll inspections and form checks were accomplished and also vibration analyses of the grinding machine were performed during the roughing and finishing operations.

The measurement points on the grinding machine are shown in fig. 3.

Figure 4 explains the vibrational behaviour by comparing the velocities (RMS [mm/s]) and the accelerations with the values of the ISO 10816 − 3/09.The detailed analysis showed a frequency of 300 Hz, attributable to electrical phenomena. In fact, two rectifiers generate voltage harmonics that are multiple of 6. The frequency of 300 Hz represents the product of the line frequency (50 Hz) multiplied by 6 (3 phases multiplied by 2). It was recognised the absence of problems in the analysed working conditions (roughing and finishing). Thus, the cause of marks was not identified in the grinding machine.

1.2. Gear box

During the rolling operations, measurements were performed radially on the gear boxes.

Figure 5 shows the accelerometer positions according to the ISO 10810 −3/09 and Figure 6 shows the velocities and accelerations measured on the gear boxes (for first and second stand) compared with the threshold values:
- the first gearbox has an acceptable vibrational behaviour: there are not critical conditions in the motor and the gearbox;
- the second gearbox has a good vibrational behaviour: the detailed analysis shows a frequency component at 108 Hz, due to tooth mesh frequency.

Thus, the results of the measurements show that the gearbox systems are not included among the causes of chatter marks.

1.3. The second stand

Since the second stand is exposed to greater loads, the analysis of the vibrations in the stands was performed only on the second one, as described in the previous paper [19]. In fact, the second stand rolls the strip already rolled by the first one, so that the material is hardened and less malleable. Furthermore, the defects created by the first stand during the rolling process are erased and overwritten completely.

For this reason, the possible origin of self-excited vibrations was identified on the second stand system. Figure 7 shows the accelerometers location on the second stand in correspondence of the housings of IMRs.

Figures 8 and 9 show the measures in the main points and for different values of the rolling speed (Figure 8 with a rolling mill speed equal to 40m/min and Figure 9 for a rolling mill speed equal to 80 m/min). In particular, the violet histograms regard the measures before the substitution of the cassettes and the blue ones regard the measures obtained after the substitution of the cassettes. One can see that the behaviour of the stand at 40 m/min has a relevant improvement with the change of the side support rolls in the cassettes. The vibration levels are greatly reduced, also for a rolling speed of 80 m/min, where the improvement is more evident. Thus, considering the results of the measurements, the criticality of the case study was found inside the stands. The frequency analysis of the stand showed the presence of a peak before the replacement of the SSR cassettes proportional to the rolling speed, as showed in [17-20].

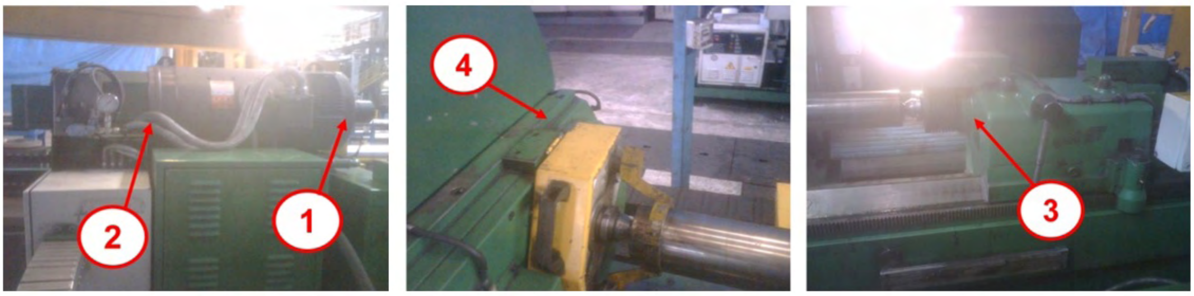

Fig. 3. Accelerometers position on grinding machine

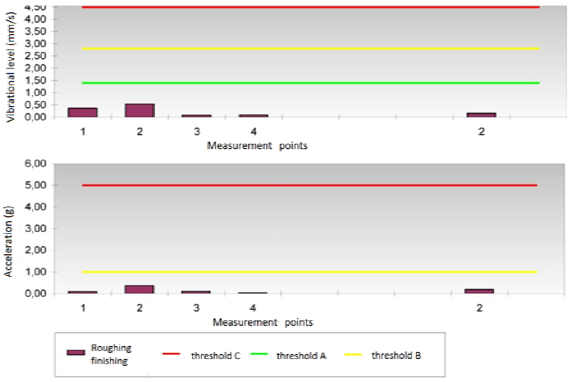

Fig. 4. Velocity and the accelerations measuring on grinding machine vs ISO value

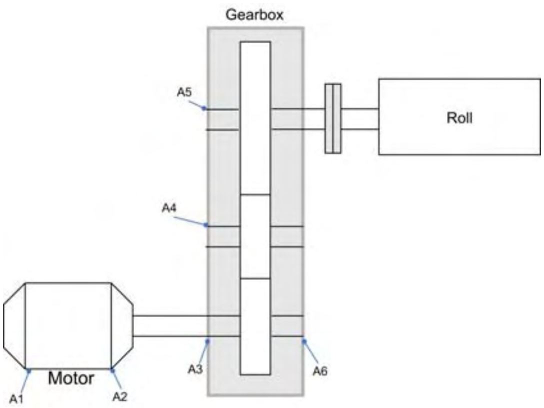

Fig. 5. Accelerometers positions on motor and gearbox

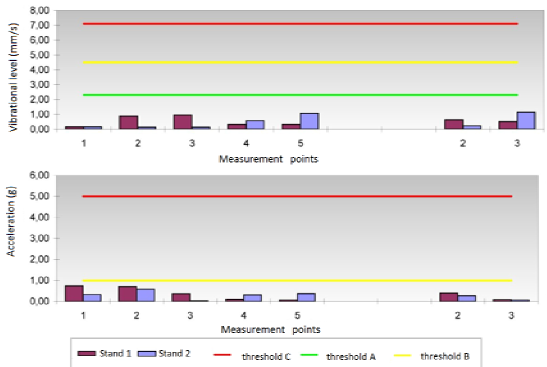

Fig. 6. Velocity and the accelerations measures on gear box vs ISO value

2. NUMERICAL MODEL WITH OROWAN

In the rolling mill plants, it is fundamental to study the behaviour of the deformation process, in order to assess the main process variables (for instance the rolling force) in all operating conditions [1]. The studied rolling mill with 6 rolls and 4 side support rolls in the cassettes was modelled with a lumped parameter model with 10 dofs. The stiffness and the damping of the mass frame connection is considered and the physical contact between rolls is described as spring with negligible damping (with the hypothesis that there is not separation between rolls when the process is running). The constants K_o and C_o represent the stiffness and the damping of the mass frame connection, K_s the stiffness of the spring in the cassettes. Then, the stiffness of the spring K_{BI}, K_{IW} and K_{WS} describing the contact rolls are defined according to the Hertz theory [4], [2] as follows:

$$K_{WS} = dF/\, d\delta_{WS} \tag{1}$$

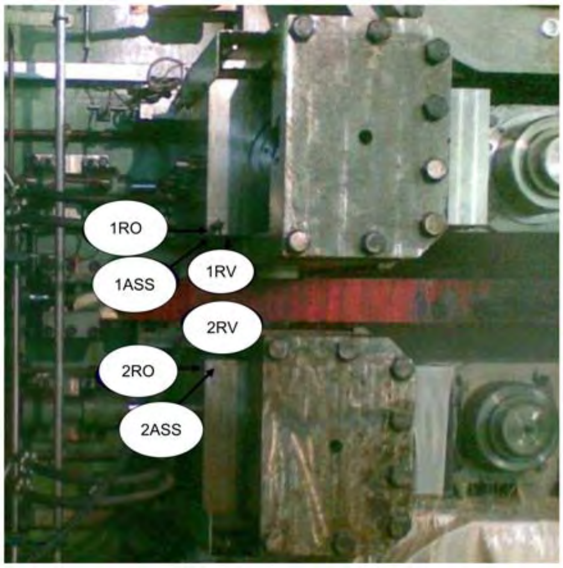

Fig. 7. Accelerometers position on stand:RO (radial horizontal), RV (radial vertical) and ASS (assial)

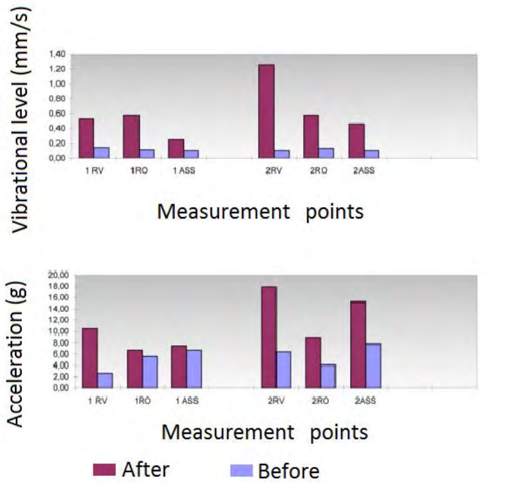

Fig. 8. Measurements at 40 m/mm of second stand

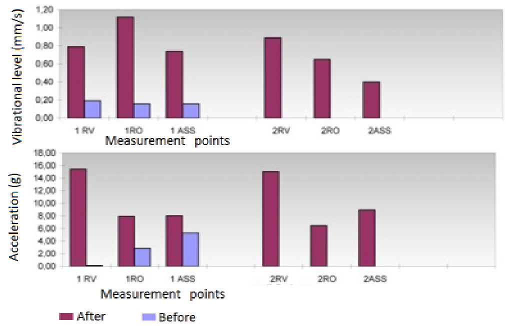

Fig. 9. Measurements at 80 m/mm of second stand

$$K_{BI} = dF/d\delta_{BI}\,,\ K_{IW} = dF/\, d\delta_{IW}$$

where F is the applied force and δij is the generic displacement between the centres of the rolls in contact, depending on the elasticity modulus, on the Poisson's ratio and on the geometry of each contacting rolls.

$$\delta_{ij} = \frac{F}{E^{*}_{ij}\pi}\left[\frac{2}{3} + \ln\left(\frac{2D_i}{b}\right) + \ln\left(\frac{2D_j}{b}\right)\right] \quad (2)$$

$$\frac{1}{E^{*}_{ij}} = \frac{\left(1-\nu_i^2\right)}{E_i} + \frac{\left(1-\nu_j^2\right)}{E_j} \quad (3)$$

$$b = c\left(\frac{\frac{F}{2}\frac{D_i D_j}{D_i + D_j}}{E^{*}}\right)^{1/2} \quad (4)$$

The parameter c value is equal to 1.60 or 2.15 depending if rolls have different or similar elasticity properties. The relationship between stiffness and load F is not linear; the exerted sheet force and the work roll displacement can be decomposed into the steady and dynamic parts:

$F = F(d) + F(s)$

$y_1 = y_1(d) + y_1(s)$

The overall dynamical response of the work roll is therefore highly dependent upon the nature and also the characteristics of the sheet force. Thus, the stiffness can be linearized without considering the dynamic term of the sheet force. In addition, the real position between the SSR and the WR should be noted.

In Figure 10 the equilibrium position and the generic configuration of SSR and WR have been represented, where the point A is the SSR centre, the point B is the WR centre and Rw is the WR radius.

The origin of y_1 and x_1 axes is the point B in equilibrium position. The elastic force can be expressed by:

$$F_E = K_{WS}\, X_1 \sin\theta_o / \sin\theta \quad (5)$$

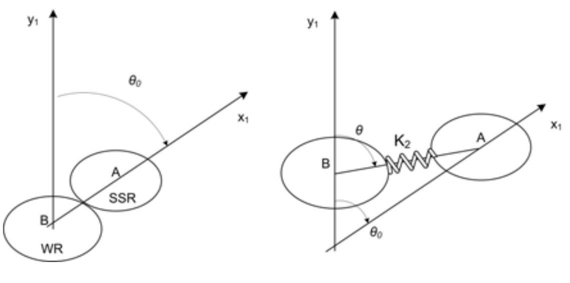

Fig. 10. Equilibrium position and generic configuration [20]

The OA segment is the displacement of the SSR cylinder, that can be defined considering the distance between the rolls centres:

$$X_1 = x_1 + R_W + R_{SSR} \quad (6)$$

Hypothesizing small displacements, the relationship will be linearized, so:

$$F_E = K_{WS}\, X_1 \quad (7)$$

Firstly, a model having ten degrees of freedom where the masses are reduced to the ten rolls involved in the process can be considered. To simplify the problem, the stand was assumed symmetrical to the rolled strip and symmetrical to the vertical axis of the stand so that the ten degrees of freedom model was reduced to the simplest system with two degrees of freedom. The rolling force F_{roll} acting between the strip and the working roll can be evaluated as a function of y_1, [7].

According to the Orowan's method and assuming inhomogeneous deformations, the rolled strip is divided, in the rolling direction, into segments of material constituted by a portion of material between two cylindrical surfaces A (Fig. 11). The rolling pressure distribution p has different expressions inside the plastic deformation region [5-10]. In the slip and in the stick zones the relationships taken from Orowan's inhomogeneous theory are respectively:

$$p = \frac{F}{h(y_1)} + \sigma_s\left[\omega(\phi, l) \pm \frac{1}{2}\left(\frac{1}{\phi} - \frac{1}{\tan\phi}\right)\right] \quad (8)$$

$$p = \left(\frac{F}{h(y_1)} + \sigma_s\omega\right)\left[1 \pm \mu\left(\frac{1}{\phi} - \frac{1}{\tan\phi}\right)\right]^{-1} \quad (9)$$

where σ_s is the yield stress of the material subjected to homogeneous compression, μ is the coefficient of friction, the function w is nonlinear and takes into account the inhomogeneity of plastic deformations inside the bite zone, according to:

$$\omega(\phi, l) = \frac{1}{\sin\phi}\int_0^{\varphi}\sqrt{1 - a^2\left(\frac{\vartheta}{\phi}\right)^2}\cos\vartheta\, d\vartheta \quad (10)$$

and F is the roll tension per unit width of the strip.

$$\frac{dF}{d\phi} = 2R_w\cos\phi(\tan\phi \pm \mu) \quad (11)$$

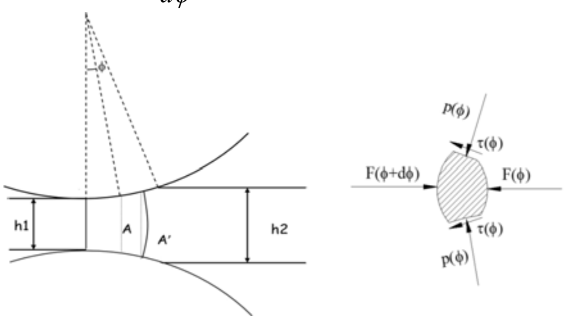

Fig. 11. Inhomogenus theory by Orowan [20]

The rolling force F_{roll} can be expressed through the integral formulas, where φ_{out} and φ_{in} represent respectively the angles to the exit and the entry section of the roll bite. The disturbances and the variations of the strip thickness due to roll vibration generate the dynamic component of the rolling force. This dynamic component deflects the structure of the stand leading to variations in the roll gap, y_1, which in turn results in further variations in the rolling force. Under certain conditions, however, this interaction between the structure and the process leads to dynamic instability.

$$F_{roll} = \int_{\varphi_{in}}^{\varphi_{out}} p\, d\vartheta \quad (12)$$

The proposed model was solved with the FRF linearized equation as presented in [19-21] and the chatter was reduced with the change of the spring stiffness in the cassettes. In this paper simulations of the roll gap versus time are presented for different values of stiffness: in fig. 12 with k = 269 N/mm and in fig. 13 with k = 485 N/mm and a force at a frequency of 125 Hz. One can see that the oscillation of the roll gap is damped with k = 485 N/mm. This result confirms what is proposed in [19].

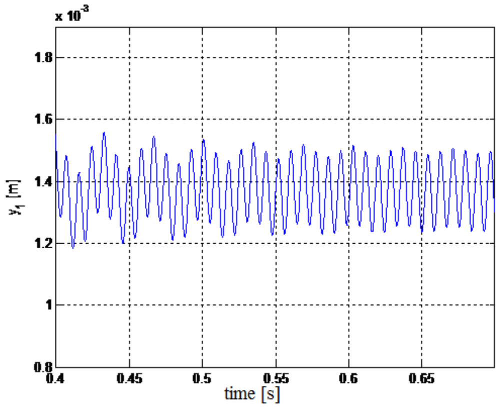

Fig. 12. Roll gap with k = 269 N/mm

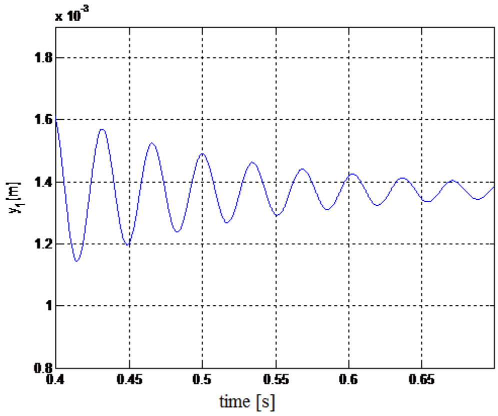

Fig. 13. Roll gap with k = 485N/mm

3. CONCLUSIONS

A chatter solution in a S6-high rolling mill was presented in [19] based on a simplified model. In this second paper a more comprehensive analysis was presented to detect the phenomena, taking into account all the steps that have been identified as causes of chatter in the cassette. In particular the vibrations analysis was completed by subsystem measurements, the velocity and acceleration values are compared with the ISO reference values. Moreover, a non-linear model based on the Orowan's method was presented and simulations were performed.

ACKNOWLEDGEMENTS

The authors wish to thank the competent consultant team of A.S.T. and in particular the engineers S. Cervo and A. Petrucci, for the careful supervision and the experimental data.

REFERENCES

[1] Cianetti F, Braccesi C, Valigi MC. Numerical Modelling and Simulation of the Hot Rolling Mill Process. Advanced Engineering Forum 2016; 15: 64-74.
[2] Gryllias KC, Antoniadis IA. Modeling and experimental analysis of a 6-High industrial rolling mill vibration response. Proc. The Seventh International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, Ettington Chase, Stratford-upon-Avon, England June, 2010: 22-24.
[3] ISO 10816-6. Mechanical vibration-evaluation of machine vibration by measurements on non- rotating parts - Part 6: Reciprocating machines with power ratings above 100 kW. 1995.
[4] Johnson RE, Qi Q. Chatter Dynamics in Sheet Rolling, Int. J. Mech. Sci. 1994; 36(7): 617-630.
[5] Kapil S, Eberhard P, Dwivedy SK. Dynamic analysis of cold-rolling process using the finite-element method. Journal of Manufacturing Science and Engineering. Transactions of the ASME 2016; 138(4): 041002.
[6] Liu X, Zang Y, Gao Z, Zeng L. Time delay effect on regenerative chatter in tandem rolling mills. Shock and Vibration 2016: 4025650.
[7] Linghu K, Jiang Z, Zhao J, Li F, Wei D, Xu J, Zhan X, Zhao X. 3D FEM analysis of strip shape during multi-pass rolling in a 6-high CVC cold rolling mill. The International Journal of Advanced Manufacturing Technology 2014; 74(9): 1733-1745.
[8] Malvezzi, M, Valigi, MC. Cold rolling mill process: A numerical procedure for industrial applications. Meccanica 2008; 43(1): 1-9.
[9] Malvezzi M. Rinchi M. Control systems of strip tension in hot steel rolling mills trains. Proc. of Nineteenth IASTED International Conference – MIC- Model- ing, Identification and Control, Innsbruck, Austria, 2000.
[10] Mehrabi RA, Salimi MB, Ziaei-Rad SB. Finite element analysis on chattering in cold rolling and comparison with experimental results. Journal of Manufacturing Science and Engineering, Transactions of the ASME 2015; 137(6): 061013-061022.
[11] Nessler GL, Cory JF. Identification of chatter sources in cold rolling mills. Iron and Steel Engineer 1993: 40-45.
[12] Orowan E. The calculation of roll pressure in hot and cold at rolling. P I Mech Eng 1943; 150: 1847-1982.
[13] Pei-Hua Hu, Huyue Zhao, Ehmann KF. Third-octave-mode chatter in rolling. Part 1: Chatter model. Proceedings of the of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2006; 220: 1267-1277.
[14] Petrucci A. Problemi vibrazionali della laminazione a freddo mediante tecnologia S6- High. Thesis degree, 2013.
[15] Roberts WL. Hot rolling of steel, Marcel Dekker, 1983, New York.
[16] Swiatonoswki A, Bar A. Parametrical Excitement vibration in tandem mills- mathematical model and

its analysis. Journal of Material Processing Technology 2003: 214-224.
[17] Tamiya T, Furui K, Hida H. Analysis of chattering phenomenon in cold rolling. Proceedings of International Conference on Steel Rolling 1980; 2: 1191-1207.
[18] Valigi MC, Cervo S, Petrucci A. Chatter Marks and Vibration Analysis in a S6- high cold rolling mill, in Proc. III Inter. Conference on Condition Monitoring of Machinery in Non-Stationary Operations (CMMN02013), 2013, Ferrara, Italy.
[19] Valigi MC, Papini S. Analysis of chattering phenomenon in industrial S6-high rolling mill. Diagnostyka 2013; 14(3): 3-8.
[20] Valigi MC, Papini S. Chatter in a S6-high rolling mill. XXI Congresso Nazionale AIMETA, 2013, Torino.
[21] Valigi MC, Cervo S, Petrucci A. Chatter marks and vibration analysis in a S6-high cold rolling mill. Lecture Notes in Mechanical Engineering 2014; 5: 567-575.
[22] Wu S, Shao Y, Wang L, Yuan Y, Mechefske CK. Relationship between chatter marks and rolling force fluctuation for twenty-high roll mill. Engineering Failure Analysis 2015; 55: 87-99.
[23] Yun IS, Wilson WRD, Ehmann KF. Review of chatter studies in cold rolling. International Journal of Machine Tools & Manufacture 1998; 38: 1499-1530.
[24] Sahu PK, Pahwa R, Nayak N. A review: On rolling lubricant optimization. Journal of Technical Reports in Engineering and Applied Science 2016; 3: 123-130.
[25] Lisini GG, Toni P, Valigi MC. H∞ control system for a four-high stand rolling mill. Proceedings of the Institution of Mechanical Engineers. Part I. Journal of Systems and Control Engineering 2000; 214(2): 79-86.

Received 2016-07-29
Accepted 2016-10-14
Available online 2016-11-21

Maria Cristina VALIGI is Associate professor of Mechanics of Machines at University of Perugia. She is graduated in Mechanical Engineering and she obtained the PhD degree from University of Bologna studying the control of rolling mills.
Her area of interest regards diagnostics of mechanical systems, modelling and simulation, tribology and dynamic models of train vehicles.

Susanna PAPINI is Researcher of Mechanics of Machines at University of Florence.
She is graduated in Mechanical Engineering and she obtained the PhD degree from University of Bologna studying the wheel and rail contact.Her area of interest regards diagnostics of mechanical systems, modelling and simulation, tribology and dynamic models of train vehicles.