

Study of the work roll cooling in hot rolling process with regard on service life

R. Zahradník, J. Hrabovský, M. Raudenský

Operational conditions and many studies confirmed that the work rolls cooling in hot rolling process have significant impact on damage and service life. The specific approach based on the numerical simulation and experimental results of the work roll cooling optimization and service life improvement is presented in this paper. The 3D finite element model was prepared for the numerical simulations of the work roll cooling. The FE model represents circular sector of the work roll. The model is fully parametric. It is capable to simulate a roll with any diameter, any thickness. Each of the model parameters can be easily changed based on user requirements. The stress state is calculated by ANSYS in two steps. At first, the thermal conditions as starting temperature of the roll, cooling intensity and so on are applied and time dependent thermal analysis is performed. The temperature field of work roll is obtained from transient thermal analysis and is used as thermal loads in second step. In the second step structural analysis is carried out. The other relevant boundary conditions as normal, shear and contact pressure are considered in structural analysis. The Tselikov load distribution model is used for normal and shear stress distribution in a rolling gap. The boundary conditions for FE analysis are prepared in software MATLAB. All considered boundary conditions are based on real measured data from hot rolling mills. The results of the performed analyses are focused on the description of the assessing methodology of the work rolls cooling on the stresses, deformations and service life of the rolls.

Keywords: Staggered array - Water jet cooling - Boiling - Hot steel plate

INTRODUCTION

Work roll surfaces for hot strip rolling suffer from considerable degradation due to high thermal shocks and additional mechanical load. These shocks and loads produce plastic strain and residual stress. This necessarily leads to nucleation of cracks and forced hot strip mill to temporary shutdown, replace work roll or even to work roll elimination.

In addition, surface layers of work rolls expose to normal and tensile stress, produced during contacts with slabs and backup rolls. Values of the normal stress in work roll surface layer can be three times higher than rolled material yield strength. Values of tensile stress in work roll surface layer can reach 80 % of rolled material yield strength [1], [2].

The most of the reasons why are work rolls replaced are connected to load detrimental effects. Cracks are induced from surface or within very thick surface layer. The highest thermal fluctuation happens in a subsurface layer with thickness around 500 μm during contact with slab. The main stress even from mechanical load happens in a subsurface layer with thickness around few millimeters

during contact with slab. It is unnecessary to model a whole work roll [4]. We can observe just problematic surface layers with sufficient accuracy and reasonable computation time. The presented model is designed with these assumptions.

The big problem associated with numerical modeling of hot rolling process is obtaining proper material properties. The most of work rolls are made from high chromium or high speed steel. These two materials are used for more than 10 years and they have the highest service life so far.

This paper is focused on determination of the stress state in the work roll surface layer under the real load condition by finite element modelling with non-linear, thermal dependent material model. Two different configurations are simulated to see the effect of chilling on stress state.

Finite element analysis

Finite element analysis (FEA) was used for results determination. The numerical analysis is divided into two coupled parts – a transient thermal and a structural analysis. The first step is the transient thermal analysis for calculation of time-dependent temperature field.

The second step is calculation of set of static structural analysis with deformation from un-homogeneous temperature field and additional loads.

R. Zahradník, J. Hrabovský, M. Raudenský
Brno University of Technology, Czech Republic

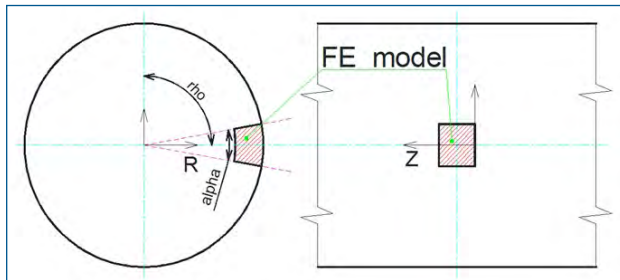


Fig. 1 - The FE model sketch and used system of axes. The red hatching represents the FE model insertion to a work roll volume.

Fig. 1 - Schema del modello FE e sistema di assi utilizzati. L'inserito rosso rappresenta l'inserimento del modello FE in un volume del rullo.

The model is fully parametric, build in APDL and capable to simulate any work roll geometric configuration. All parameters of the FE analysis are driven by the MATLAB script.

MATERIAL MODEL

The use of nonlinear, thermal depended properties is necessary. Most of the used material properties were measured by Heat transfer and fluid flow laboratory. The stress-strain curves of middle range quality of high speed steel in the Fig. 5 are result of cooperation of Heat transfer and fluid flow laboratory and its industrial partners. Instead of direct measurement, a values of hardness like function of temperature were measured. These hardness values were recalculate into ultimate tensile strength and

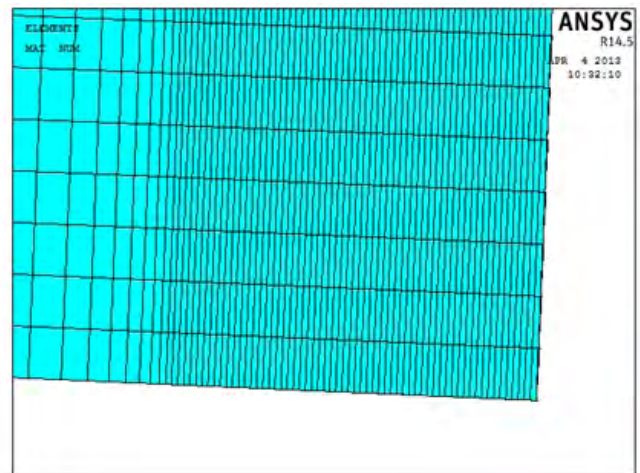
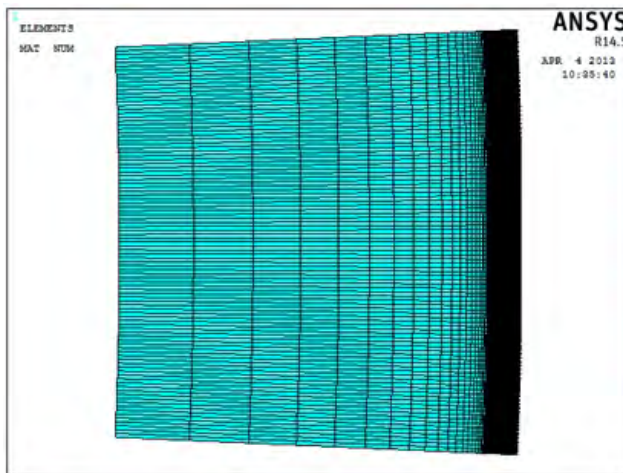


Fig. 2 - The preview of the FE model and FE mesh sizing.

Fig. 2 - Antepima del modello FE e dimensionamento del reticolo FE.

The boundary conditions are prepared with a special script in MATLAB. This script asks for necessary inputs and produces ultimate boundary condition for ANSYS. These files are loaded into ANSYS, calculated and results are automatically exported.

NUMERICAL MODEL DESIGN

The Fig. 1 represents a drawing of the FE model which is used for calculation in FEA. The R-axis dimension is addressed like "the thickness" of the FE model, the Z-axis dimension is addressed like "the height" of the FE model and the dimension α represents central angle.

The FE model represents the 5° angular cylindrical sector and it is created like a surface layer with the thickness of 27 mm - the red hatched area in the Fig. 1. The height of the FE model is 1 mm in axial direction.

FE mapped mesh is purposely used for whole model. The SOLID70 and SOLID185 element type are used in the thermal analysis and the structural analysis, respectively.

yield strength like function of temperature. The curves in Fig. 5 were interpolated based on the knowledge of general knowledge of stress-strain curve shape for high speed steel and based on the relation between the ultimate strength, yield strength and hardness [1]. The stated values could be different from the real high speed steel performance. Because of the wide range of variation among different materials, it is not possible to state confidence limits for the errors.

The Fig. 3, the Fig. 4 and the Fig. 5 shows used thermal conductivity, specific heat and density in range of 20°C to 600°C . Measurements were performed on several test samples and averaged.

BOUNDARY CONDITION

The thermal and the structural analysis are connected together. They are using same FE geometrical model and mesh but different boundary conditions.

The thermal analysis uses three different boundary con-

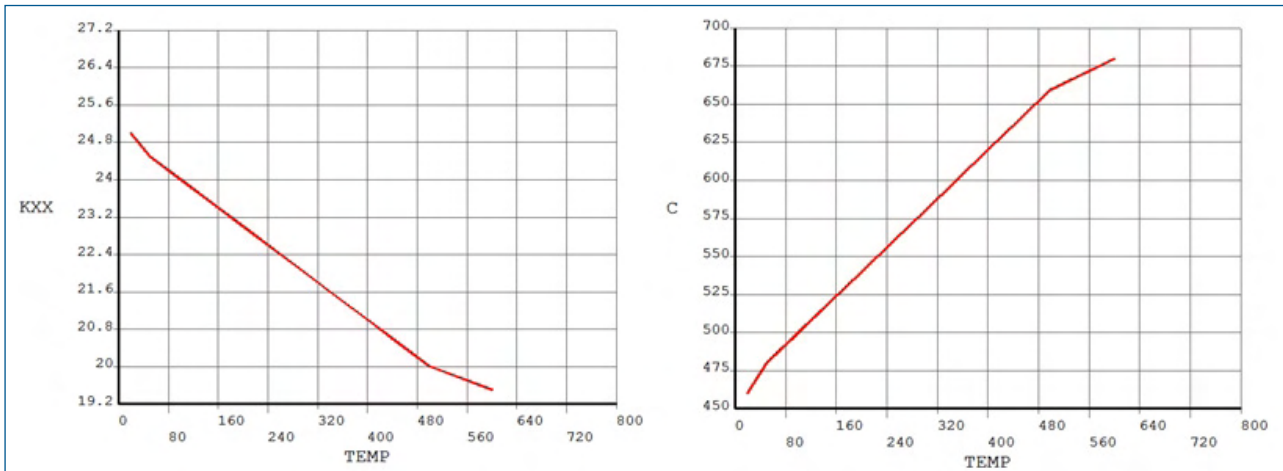


Fig. 3 - Material properties used in simulations: thermal conductivity (a) and specific heat (b).

Fig. 3 - Proprietà dei materiali usati nelle simulazioni: conducibilità termica (a), e calore specifico (b).

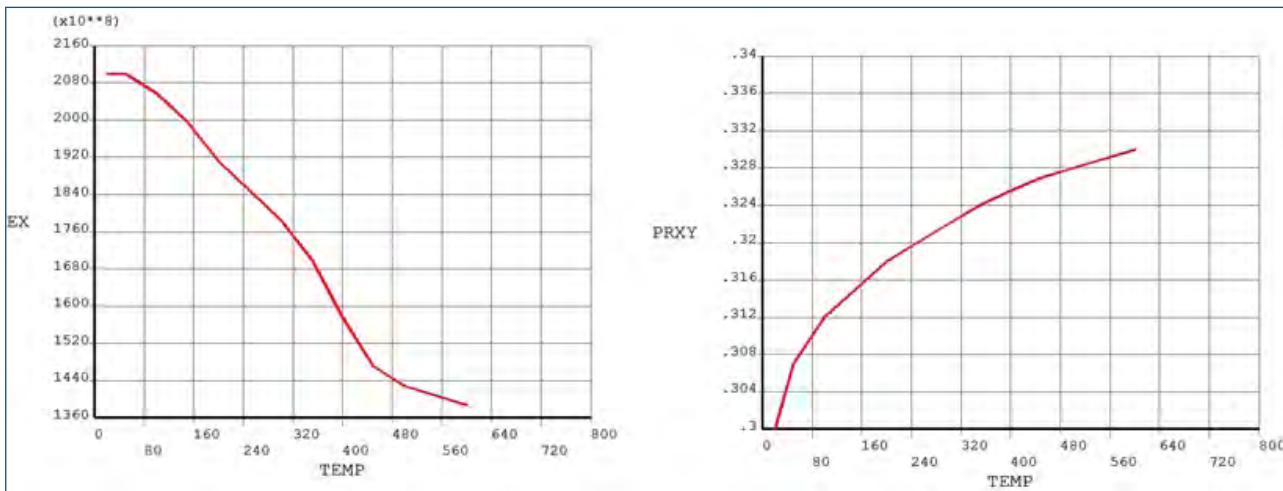


Fig. 4 - Material properties used in simulations: Young's module of elasticity (a), Poisson ratio (b).

Fig. 4 - Proprietà dei materiali utilizzate nelle simulazioni: modulo di elasticità di Young (a), coefficiente di Poisson (b).

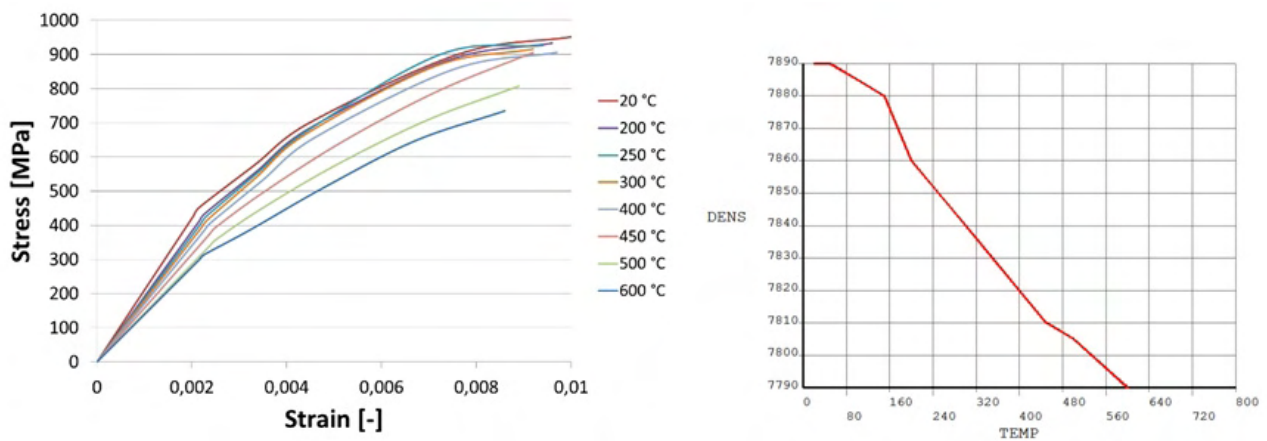
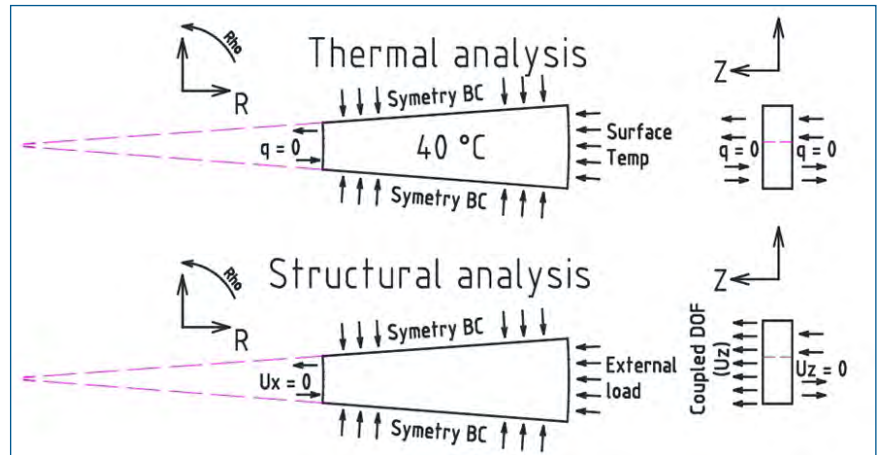


Fig. 5 - Material properties used in simulations: stress-stain behavior for different temperature (a) and density (b).

Fig. 5 - Proprietà dei materiali utilizzate nella simulazione: comportamento sforzo-deformazione per diverse temperature (a) e densità (b).

Fig. 6 - A preview of the FE model and FE mesh sizing.

Fig. 6 - Anteprima del modello FE e dimensionamento del reticolo FE.



ditions. The first boundary condition is an applied time depended surface temperature on the plane which represents a work roll surface. The second boundary condition is a symmetry of model - heat flux into or from the FE model is equal to zero. This boundary condition is based on presumption that the simulated even is very fast, the influenced volume is very small compare to whole model volume and the temperature is acceptable homogenous in a circle sector vicinity. Thanks to these facts, we can neglect the side heat fluxes. The initial condition is uniform temperature field in the FE model volume.

Result from the thermal analysis is basic load field for the structural analysis. The structural analysis uses symmetry on the same planes like the thermal analysis. A normal and a shear surfaces stress are applied on the plane which represents work roll surface. The nodes with $Z = 0$ are fully constrained and the nodes with $Z = 1$ mm (full height of the FE model) are coupled together. Summarization of all used boundary condition can be found in the Fig. 6.

A residual stress from work roll manufacturing is not included.

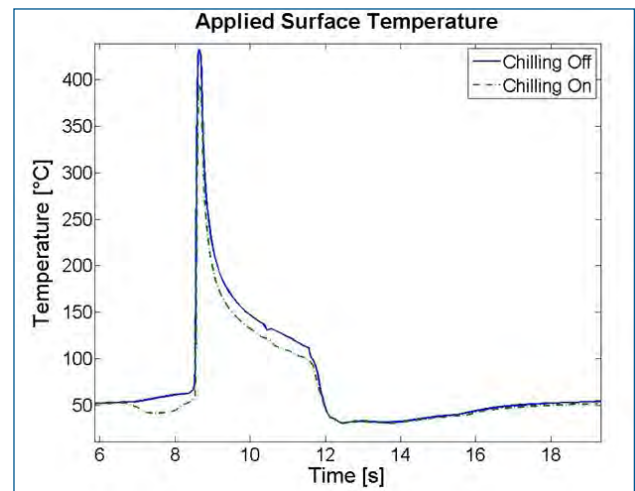


Fig. 7 - The comparison of applied surface temperature for both simulated configuration.

Fig. 7 - Confronto fra le temperature superficiali applicate per entrambe le configurazioni simulate.

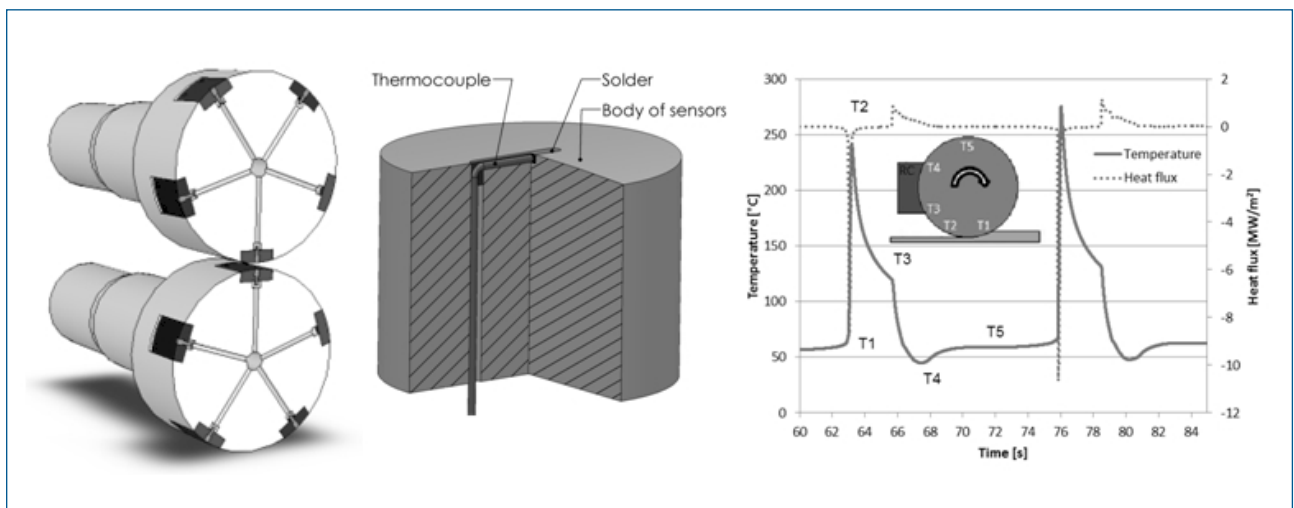


Fig. 8 - Cross-section of the work rolls with the inserts HSS materials and the holes for thermocouple wires (a), temperature sensor sketch (b) and recorded thermal cycles (c).

Fig. 8 - Sezione trasversale dei rulli di laminazione con gli inserti di materiali HSS e i fori per i cavi delle termocoppie (a), schema dei sensori di temperatura (b) e cicli termici registrati (c).

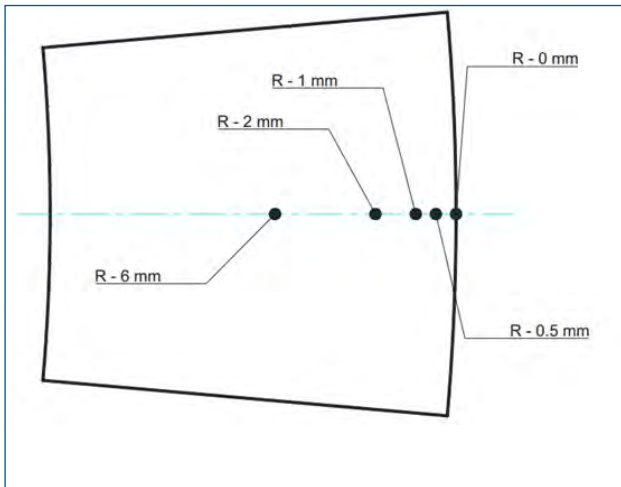


Fig. 9 - Scheme of points where the result were taken from the FE model.

Fig. 9 - Schema dei punti nei quali sono stati presi i risultati del modello FE.

Thermal boundary condition is applied on the model as time depended roll surface temperature which was obtained from experimental measurement in rolling mill. The temperatures were measured in five different points around work roll diameter with two different types of temperature sensors in two different depths (0.4 and 0.8 mm from surface). The surface temperatures were calculated by inverse task.

The five hours of rolling was measured. Two similar cases were chosen for the simulation in this paper. Both configuration has same rolling speed, reduction and cooling inten-

sity. The difference between them is chilling status – on/off. Chilling is term for spraying water, lubricant or both of them into the rolling gap (or the surface of work roll) just before it enters rolling gap. The Fig. 7 shows the applied surface temperature for chosen cases. The details about this measurement can be found in [6] and [7].

The main load in the structural analysis is from the non-uniform temperature field. This field is loaded in every calculation step together with additional structural loads. Additional structural loads were calculated based on Tselikov's work published in [1], [2] and [3]. The structure loads consist of normal and shear surface stresses inside the rolling gap and contact pressure between work roll and backup roll.

Results

All presented values are taken from specific nodes. These nodes are placed in the plane of the FE model symmetry. They are 0/0.5/1/2/6 mm under the surface and in charts their signatures are R – 0 mm, R – 0.5 mm, R – 1 mm, R – 2 mm and R – 6 mm, respectively.

The temperature over time, the von Mises stress, the 1st, the 2nd and the 3rd principal stress for R – 0 mm and R – 0.5 mm points, the von Mises elastic/plastic strain are exported like result for further analysis. Every figure has two charts from two simulated configurations – the chilling off and on configuration on the left and on the right, respectively.

The Fig. 9 shows one revolution of the work roll during rolling campaign. The Fig. 10 to the Fig. 14 have limited time corresponding with interval about 1/12 of one revolution of the work roll. This interval is crucial to find effect of chil-

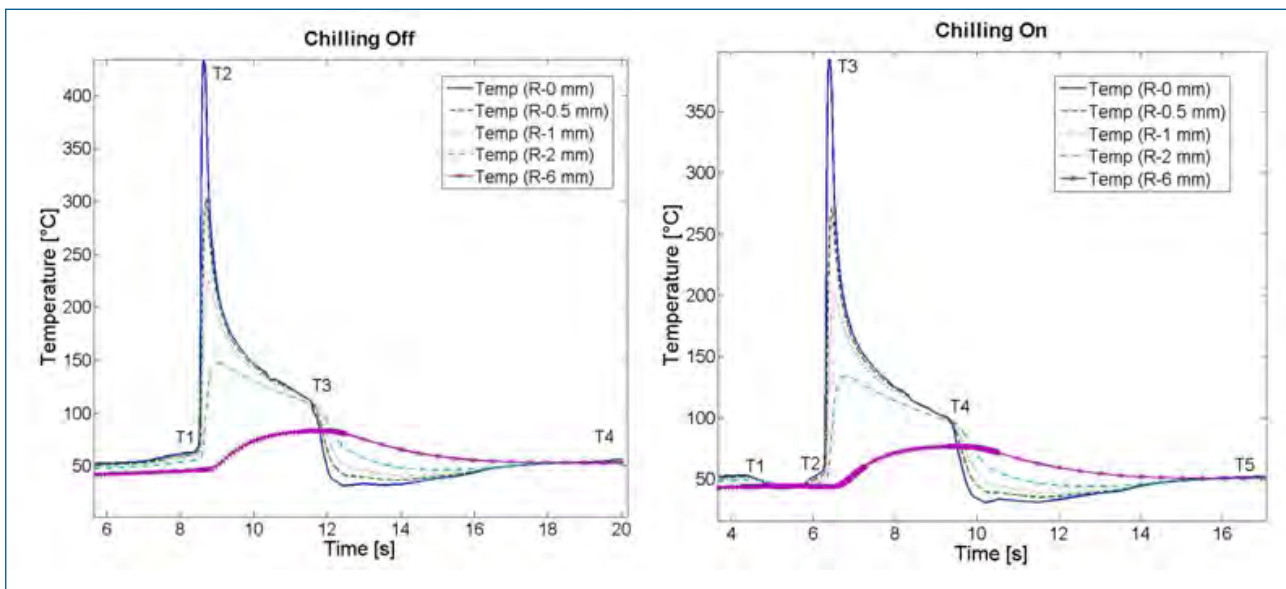


Fig. 10 - The temperature in 0, 0.5, 1, 2 and 6 mm depth from the surface for chilling off (a) and chilling on configuration (b).

Fig. 10 - La temperatura a una profondità di 0, 0.5, 1, 2 e 6 mm dalla superficie per le configurazioni chilling off (a), e chilling on (b).

Fig. 11 - The von Mises stress in 0, 0.5, 1, 2 and 6 mm depth from the surface for chilling off (a), and chilling on configuration (b).

Fig. 11 - La deformazione plastica di von Mises a una profondità di 0, 0.5, 1, 2 e 6 mm dalla superficie per le configurazioni chilling off (a), e chilling on (b).

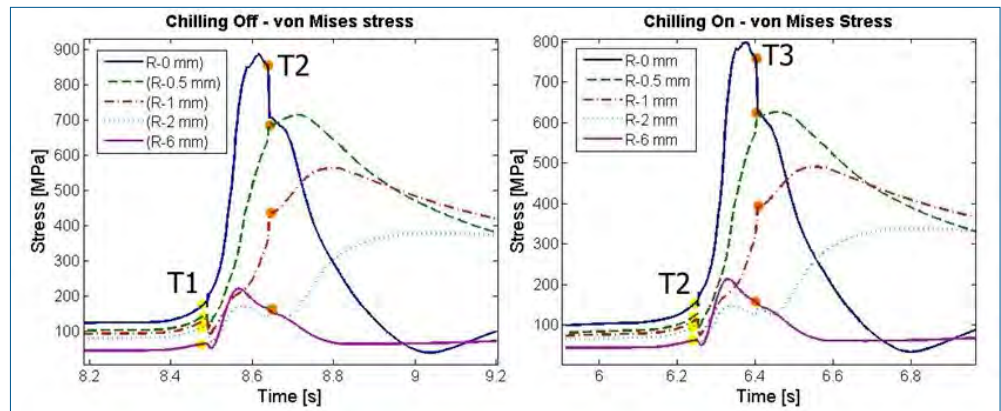
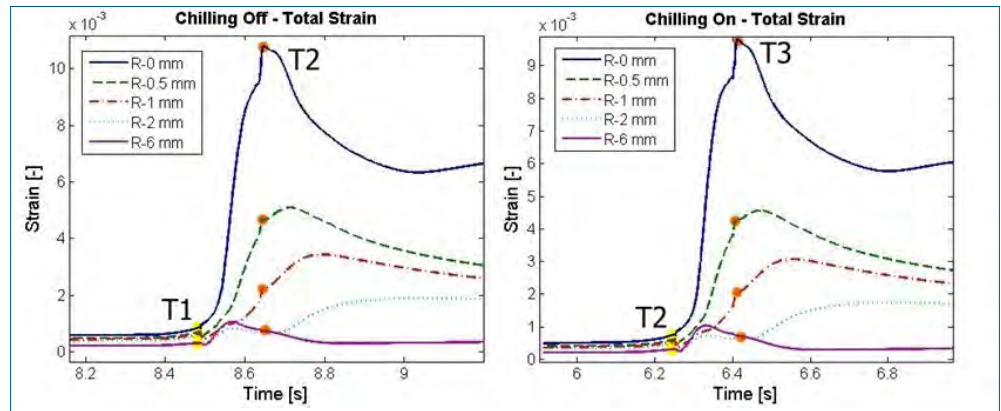


Fig. 12 - The total von Mises strain in 0, 0.5, 1, 2 and 6 mm depth from the surface for chilling off (a), and chilling on configuration (b).

Fig. 12 - La deformazione plastica totale di von Mises a 0, 0.5, 1, 2 e 6 mm di profondità dalla superficie per le configurazioni chilling off (a), e chilling on (b).



ling on service life. The most of plastic strain happens in this interval [5]. The less amount of plastic strain produced during contact with slab leads to higher service life. The Fig. 9 shows the temperature for five different depths over one work roll revolution. We can see the difference in peak temperature. The chilling caused about 10 °C difference in surface temperature before it enters rolling gap. This difference produced about 35 °C difference in peak temperature. The chilling effect was unrecognizable in the 6 mm depth.

The Fig. 10 shows the von Mises stress in 5 different depths. The points of interest from the Fig. 9 are marked by color dots. We can see time lag in peak values of von Mises stress for different depths. The contact load produce more the von Mises stress in the 6 mm depth than the heating from slab.

The Fig. 11 shows the amount of total von Mises strain. We can see that a half total strain in 0.5 mm depth compare to a surface total von Mises strain. The total von Mises strain is almost zero in the 6 mm depth.

The Fig. 12 shows the amount of von Mises plastic strain in 5 different depths. No von Mises plastic strain is produced in 2 mm depth from work roll surface in both simulated configurations. The plastic strain remains static until the work roll surface enters the cooling section where is slightly decreased but not eliminated [6]. Further work roll revolutions produce additional plastic strain which is accumulated in surface layer.

The Fig. 13 shows the principal stresses for the surface point. We can see same shapes of the curves and similar peak values - 1140 MPa and 1055 MPa for chilling off and on configuration, respectively.

The Fig. 14 shows the principal stresses in 0.5 mm depth from the surface. Again, we can see same shapes of the curves and similar peak values - 825 MPa and 766 MPa for chilling off and on configuration, respectively.

The peaks are caused by rapid heating from slab in rolling gap. The work roll surface enters rolling gap with the surface temperature about 50 °C. The surface is heated immediately. This heating produce expansion of volume in surface layer and cause the compressive stress. When surface exits rolling gap, it isn't heated anymore and heat is conducted into the work roll. The surface temperature drops down, the elastic strain, von Mises stress as well.

As we can see on the Fig. 13 and the Fig. 14, the stresses are situated in compressive stress area. They change to the tensile stress area after work roll surface passes cooling section.

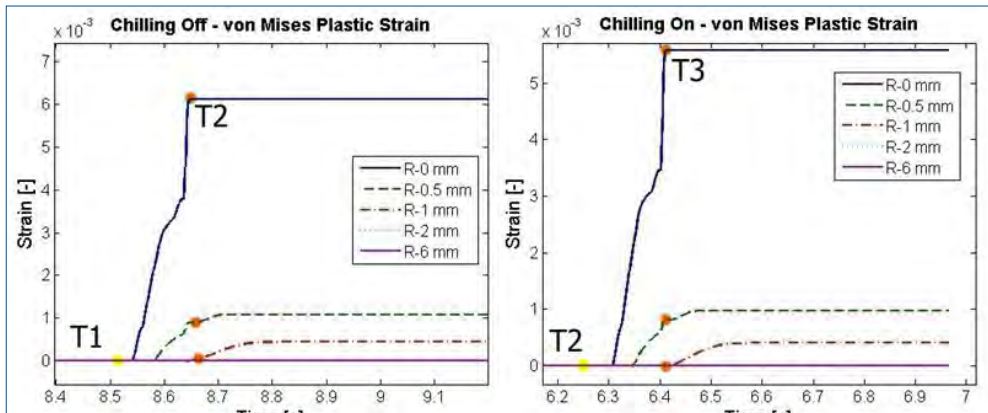


Fig. 13 - The plastic von Mises strain in 0, 0.5, 1, 2 and 6 mm depth from the surface for chilling off (a), and chilling on configuration (b).

Fig. 13 - La deformazione plastica di von Mises a 0, 0.5, 1, 2 e 6 mm di profondità dalla superficie per le configurazioni chilling off (a), e chilling on (b).

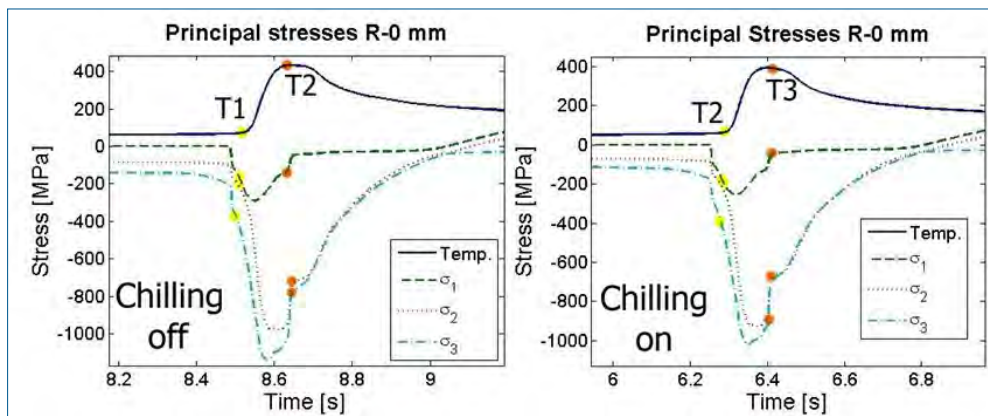


Fig. 14 - The principal stresses of surface for chilling off (a), and chilling on configuration (b).

Fig. 14 - Le tensioni principali della superficie per le configurazioni chilling off (a), e chilling on (b).

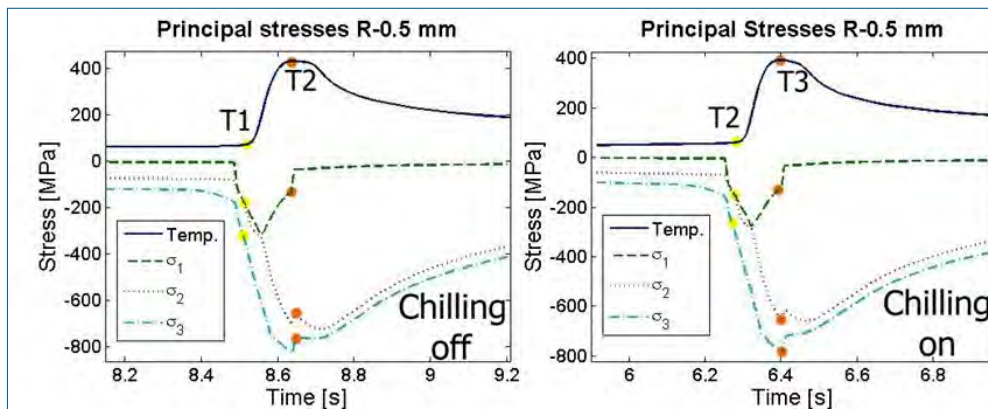


Fig. 15 - The principal stresses in 0.5 mm depth from the surface for chilling off (a), and chilling on configuration (b).

Fig. 15 - Le tensioni principali a 0.5 mm di profondità dalla superficie per le configurazioni chilling off (a), e chilling on (b).

CONCLUSION

The specific study of work roll cooling in hot rolling process was presented in this paper. The specific approach for numerical simulation of work roll surface layer stress state was used for obtaining results. This approach was also presented in this paper.

The two different configuration were simulated - with and without the chilling. The boundary condition are taken from experimental measurement. The simulations show that 10 °C difference in work roll surface temperature before it enters rolling gap produce about 85 MPa lower von Mises stress and about 5 $\cdot 10^{-4}$ lower plastic strain on exit side of rolling gap. This indicates that cooling of work roll surface before it enters rolling gap has beneficial effect for

service life but the effect is limited. Optimization of entry cooling could reduce rolling mill running cost but can't dramatically increase service life of work rolls.

ACKNOWLEDGEMENTS

The paper presented has been supported by the project No. CZ.1.07/2.3.00/20.0188,

HEATEAM-Multidisciplinary Team for Research and Development of Heat Processes.

REFERENCES

- [1] PAVLINA and C. J. Van TYNE. Correlation of Yield Strength and Tensile Strength with Hardness for Steels. *Journal of Materials Engineering and Performance*, 2008, vol. 17 Issue 6, pp. 888-893, Springer US. ISSN 1544-1024.
- [2] GINZBURG, Vladimir B. and Robert BALLAS. *Flat rolling fundamentals*. New York: Marcel Dekker; 2000. ISBN 0-8247-8894-X.
- [3] TSELIKOV, A. *Stress and Strain in metal rolling*. University Press of the Pacific, 2003. ISBN 978-1410209771
- [4] TSELIKOV, A. and V. V. Smirnov. *Rolling Mills*. Pergamon Press, 1965.
- [5] BENASCIUTTI, D., BRUSA E. and G. BAZZARO. Finite elements prediction of thermal stresses in work roll of hot rolling mills. In: *Procedia Engineering*. [Amsterdam]: Elsevier Ltd., 2010, Vol. 2(1), pp. 707-716.
- [6] ZAHRADNÍK, Radek and Miroslav RAUDENSKÝ. Minimization of thermal cracks of rolls by cooling optimization. In: *Conf. proceeding METAL 2012*. 1st Edition 2012. 2012. s. 1-6. ISBN: 978-80-87294-29- 1.
- [7] RAUDENSKÝ, M.; HORSKÝ, J.; ONDROUŠKOVÁ, J.; VERVAET, B. Measurement of Thermal Load on Working Rolls during Hot Rolling. *Steel research international*, (Online), 2013, vol. 84(3), p. 269-275. ISSN: 1869- 344X.
- [8] ONDROUŠKOVÁ, J.; POHANKA, M.; VERVAET, B. Heat-flux computation from measured- temperature histories during hot rolling. *Materiali in tehnologije*, 2013, vol. 47(1), p. 85-87. ISSN: 1580- 2949.

Studio del raffreddamento del rullo nel processo di laminazione a caldo con riferimento alla vita in servizio

Parole chiave: Laminazione - Simulazione - Processi

Le condizioni operative e molti studi hanno confermato che il raffreddamento dei rulli nel processo di laminazione a caldo ha un impatto significativo sul danneggiamento e la loro vita in servizio. In questo documento viene presentato l'approccio specifico basato sulla simulazione numerica e sui risultati sperimentali dell'ottimizzazione del raffreddamento della gabbia di laminazione e del miglioramento della vita in servizio. È stato preparato un modello 3D agli elementi finiti per la simulazione numerica del raffreddamento del rullo. Il modello FE rappresenta la sezione circolare del rullo. Il modello è completamente parametrico. Esso è in grado di simulare un rullo di qualsiasi diametro e qualsiasi spessore. Ogni parametro del modello può essere facilmente modificato in base alle esigenze degli utenti. Lo stato tensionale è stato calcolato in due fasi mediante il programma ANSYS. In un primo momento vengono impostate le condizioni termiche come la temperatura di partenza del rullo, l'intensità di raffreddamento e così via, e viene eseguita l'analisi termica in funzione del tempo. Il campo di temperature del rullo di lavoro è stato ottenuto mediante analisi termica del transitorio ed è stato utilizzato come carico termico nel secondo passaggio. Nella seconda fase sono state effettuate analisi strutturali. Come di norma, le altre condizioni di rilievo, pressione di taglio e di contatto, sono state considerate nell'analisi strutturale. Il modello di distribuzione del carico Tselikov è stato utilizzato per calcolare la distribuzione della tensione normale e tangenziale in una luce fra i rulli di laminazione. Le condizioni al contorno per l'analisi FE sono stati preparati mediante software MATLAB. Tutte le condizioni al contorno considerate nel presente lavoro sono basate su dati reali misurati in laminatoi a caldo.

I risultati delle analisi effettuate puntano l'attenzione sulla descrizione della metodologia di raffreddamento dei rulli di lavoro in termini di tensione, deformazione e durata dei rulli.