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Tools for continuous improvement of the plate quenching process★

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Key words:
Flatness; quenching; water cooling; residual stress; heat flux; plate; FEM

Abstract – Over the past few years several technical efforts have been focused on continuous improvement of quench and tempered product at ArcelorMittal Burns Harbor plate mill facility with particular attention being given to optimization of the flatness of quenched product. Incremental improvement in quench line equipment and practices is being aided by computer-based modelling tools and specialized instrumentation. The paper describes the development of different tools used to control flatness after quench and tempering units. The detailed description of a 3D model designed to predict distortion such as edge waves, center buckles, longbows and crossbows during quenching is presented. The model developed with Abaqus is able to predict the evolution of plate temperature, thermal stresses, strains, and distortions during cooling. The water cooling system is represented by top and bottom movable surfaces where a heat flux depending on width, length and temperature is applied. The effect of phase transformation is approximated by a variation of the plate thermal expansion coefficient.

Mots-clés :
Planéité ; trempe ; refroidissement à l'eau ; contraintes résiduelles ; flux thermique ; tôle forte ; éléments-finis

Résumé – Outils pour l'amélioration continue du procédé de trempe des tôles fortes. Au cours des quelques dernières années de nombreux efforts techniques ont été consacrés à l'amélioration continue des produits trempés et revenus à la tôlerie forte d'ArcelorMittal Burns Harbor, une attention particulière étant portée à l'optimisation de la planéité du produit trempé. L'amélioration incrémentale des équipements et des pratiques opératoires de la ligne de trempe a bénéficié de l'aide d'outils de modélisation numérique et d'instrumentation spécialisée. Le présent article décrit le développement des différents outils mis en œuvre pour maîtriser la planéité du produit après les unités de trempe et revenu. On présente une description détaillée du modèle 3D permettant de prédire les défauts susceptibles d'affecter la tôle lors de la trempe, tels que bord long, centre long, tuile, cintre. Le modèle, développé sous Abaqus, est capable de prédire l'évolution de la température de la tôle, des contraintes thermiques, des déformations et des distorsions au cours du refroidissement. Le système de refroidissement par eau est simulé par des surfaces supérieure et inférieure mobiles, sur lesquelles est appliqué un flux thermique dépendant de la longueur, de la largeur et de la température. L'effet des transformations de phases est approximé par une variation du coefficient d'expansion thermique de la tôle.

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Shape defects as edges waves, center buckle, longbows and crossbows are created easily during water cooling. These problems are particularly acute in thin plates The mechanism of flatness deterioration due to water cooling is not well understood. It causes operational trouble and can result in poor quality of product and productivity loss for repairing. The performances required on steel plates in recent years in terms of higher strength, improvement of the weldability, and higher quality of flatness become increasingly severe.

Based on this background, ArcelorMittal Global R&D has developed tools for continuous improvement of steel plate, including

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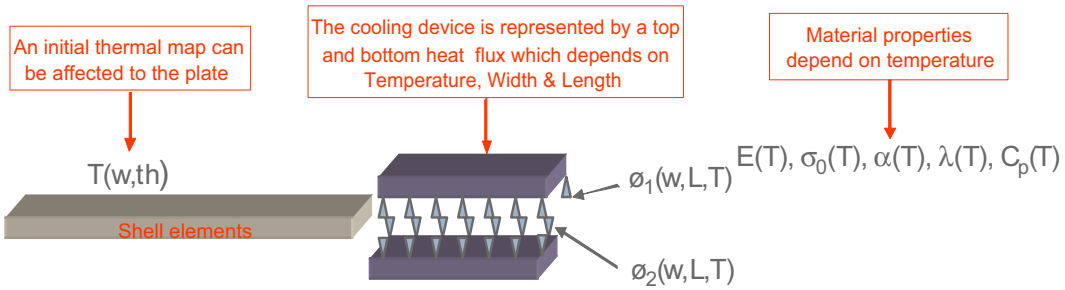


Fig. 1. Three-dimensional Thermo Mechanical Model for Quenching Process (TMMQP).
Fig. 1. Modèle thermomécanique 3D du procédé de trempe.

new flatness measurement, quench model and a three dimension finite element model (3D-FEM). The 3D model developed with Abaqus is able to predict the evolution of a steel plate temperature, thermal stresses, strains, and distortions during cooling. Figure 1 shows the position of hot plate before cooling. The heat flux in longitudinal and transversal direction is also considered [1].

Where the material proprieties depend on the temperature (T) [2]:
$E(T)$: Young modulus, $\sigma 0(T)$: Yield stress
$\alpha(T)$: Conductivity of the steel
$\lambda(T)$: Thermal expansion
C_p (T): Specific capacity
$T(w, th)$: Initial temperature profile depends on the width and the thickness
$\Phi 1$: Heat flux at the top surface
$\Phi 2$: Heat flux at the bottom surface

An initial temperature map can be given to the plate and material properties of plate depend on temperature. In this study the temperature of hot plates before cooling is considered to be uniform at $T = 900$ °C, Figure 2 shows an example of material proprieties.

The thermal expansion coefficient λ (°C) relates the change in a material's linear dimensions to a change in temperature. It is the fractional change in length per degree of temperature change. We may write:

$$\lambda = 1/L.dL/dT$$

where L is the linear dimension (e.g. length) and dL/dT is the rate of change of that linear dimension per unit change in temperature. In order to take into account the effect of phase transformation austenitic to martensite, we suppose a variation of thermal expansion at $T = 440$ °C.

1 Heat flux properties and typical boiling curves

For each cooling zone, different evolutions of heat flux are considered. The heat flux is introduced as a function of surface temperature. Figure 3a shows the Burns Harbor quench unit.

For each pressure zone we can describe different cooling modes: film boiling, transition boiling and nucleate boiling as illustrated in the Figure 3b:

- Nucleate boiling: in this regime, the cooling water is in direct contact with the steel, and heat transferred by generation of bubbles is very efficient [2].
- Transient boiling: the cooling power increases as plate temperature decrease. This means that any temperature differences which existed before cooling are amplified during this mode.
- Film boiling: during film boiling, a film of steam is formed between the steel and the cooling water, and heat is transferred through this steam film.

At the start of plate cooling film boiling is predominant. However, as surface temperature decrease, the steam film becomes unstable, the cooling water begins to come into direct contact with plate locally, and boiling gradually shifts to nucleate boiling [3].

All these phenomena are closely connected to the cooling technology used. So in order to simulate properly distortions during quenching process we determine the

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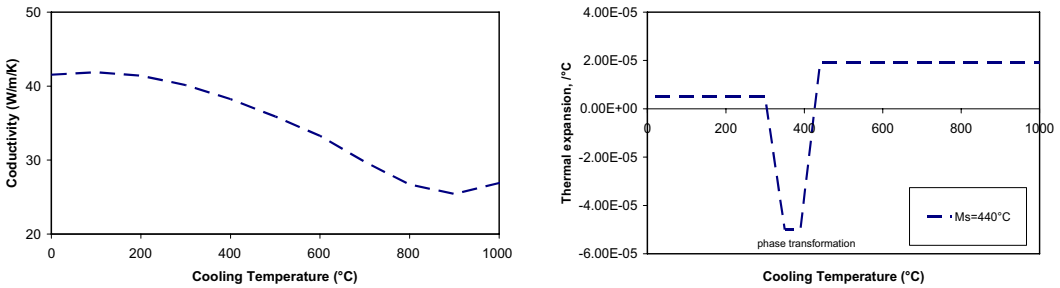
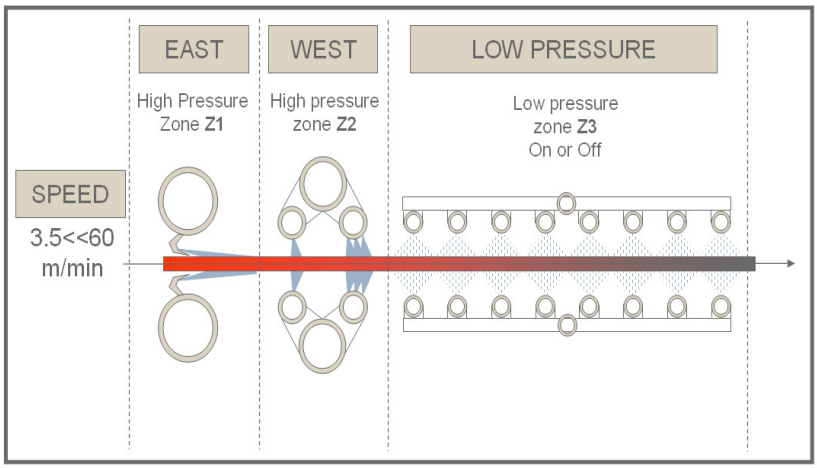
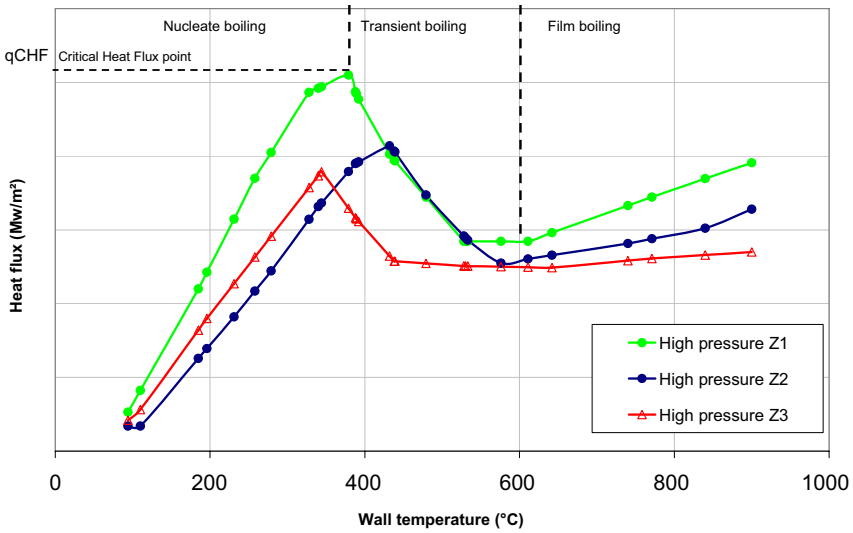


Fig. 2. Example of material properties: conductivity and thermal expansion.
Fig. 2. Example de propriétés du matériau : conductivité et expansion thermique.



(a)



(b)

Fig. 3. (a) Burns Harbor quench unit. (b) Heat flux for each pressure zone (typical boiling curves).
Fig. 3. (a) L'unité de trempe de Burns Harbor. (b) Flux thermique dans chaque zone de pression (courbes d'ébullition typiques).

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Table 1. Simulations conditions.
Tableau 1. Conditions de la simulation

Thickness = 50 mm T = 900 °C uniform	Simulated cases	plate speed (mm/s)	Ratio r (Φtop-Φbottom)/Φbottom	Temperature after cooling (°C)
Effect of plate speed (mm/s)	Case n°1	50	5%	32
	Case n°2	150		100
	Case n°3	250		203

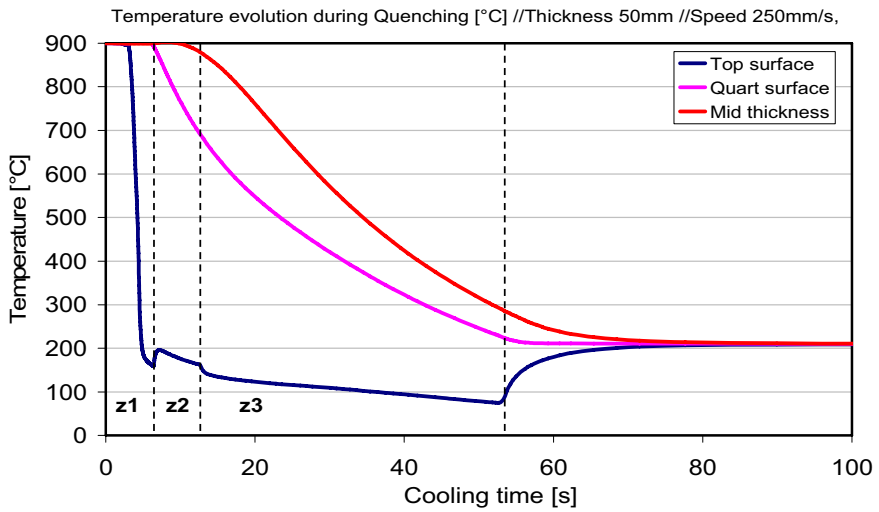


Fig. 4. Temperature evolution during quenching for each pressure zone.
Fig. 4. Évolution de la température au cours de la trempe dans chaque zone de pression.

boiling curve for our equipment through trials or CFD calculations.

2 Results of three-dimension model

The model can be used to evaluate the dissymmetry [1] cooling between top and bottom surface, the effect of plate thickness and the effect of edge masking system. This paper presents the effect of plate speed.

2.1 Simulation conditions

The geometry of the plate is 50 mm thickness, 2500 mm width and 10 000 mm in length. The initial temperature of the plate is to be uniform and equal at 900 °C. With the model we can describe also non uniformity of temperature across width and the thickness direction. The plate's speed adjusted in order to obtain good metallurgical properties. But some observations in our plants show that the speed has a big impact on flatness defects. That's why in this paper we describe the effect of the plate's speed as showed in the Table 1.

2.2 Thermal analysis

As illustrated in the Figure 4 these calculations are done for the quench unit which has three cooling zones that can be set up independently:

- Two zones with high cooling intensity in order to cool the plate surface as quick as possible; $z1$ and $z2$.
- One zone with lower intensity, to maintain the plate surface at low temperature and let the cooling front diffuse into the core $z3$.

The temperature distribution at top and middle surface calculated by finite elements method is given by the Figures 5 and 6. Result shows that the temperature of the top surface depends highly on the plate's speed Figure 5. However, the temperature in the plate at the mid thickness is the same during

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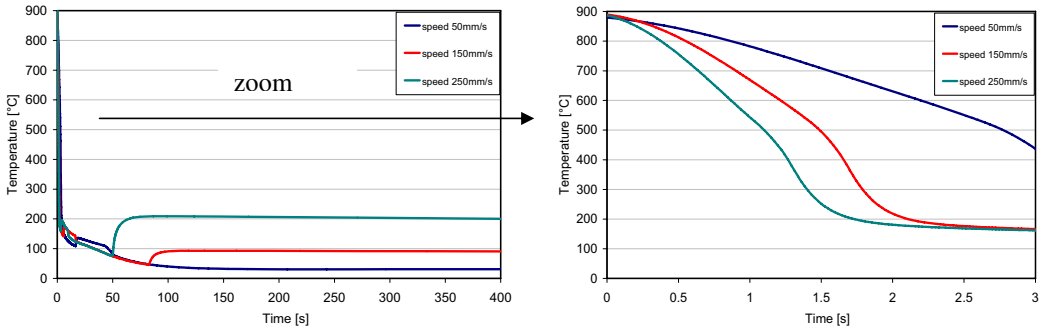


Fig. 5. Temperature evolution during quenching process at top surface and the zoom in the high pressure zone.
Fig. 5. Évolution de température de la face supérieure pendant la trempe, et zoom sur la zone de haute pression.

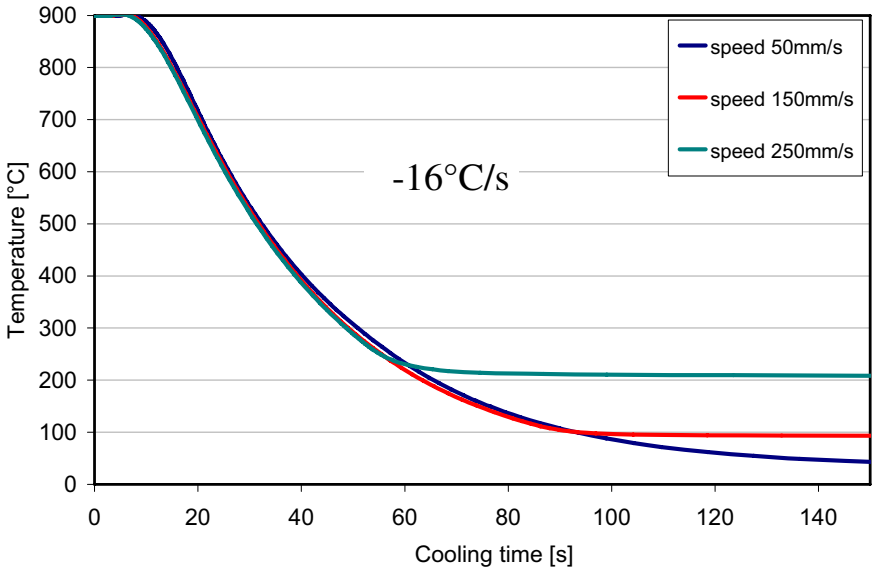


Fig. 6. Temperature evolution during quenching process at the mid thickness.
Fig. 6. Évolution de temperature à mi-épaisseur pendant la trempe.

cooling and becomes constant at exit of the quenching device. As we can see on the Figure 6 the cooling rate at the mid thickness is equal at –16 °C/s.

2.3 Stresses and strain analysis

The stress and strain are considered in the three dimensions; longitudinal, transversal and thickness direction. The cross section is assumed to be a shell. The stress and strain are assumed to be zero in all elements before cooling. Next step is to see the impact of the speed in the distortions and internal stress.

For the thick plate we notice that the distortions observed were crossbow and longbow, and that the vertical displacement increases when the speed of the plate increases. For example we have a maximum displacement equal to 6 mm for 250 mm/s and 1.5 mm for 150 mm/s at the center of the plate.

As we can see in the Figure 8b, the internal stress increases also.

As result of this distribution of internal stress across the width, it is expected that the material at the edges is more contracted than that at the center of the plate, i.e. the section located towards the edge will be longer at

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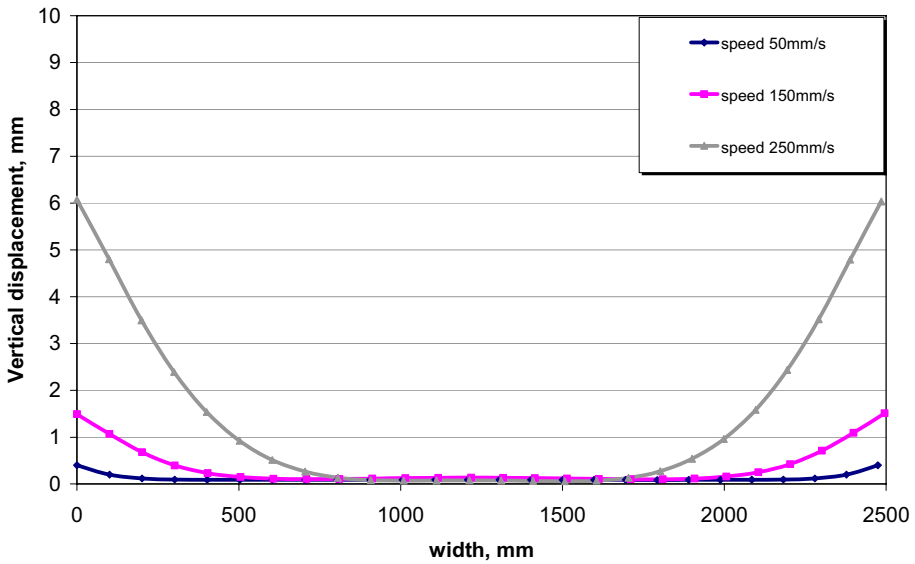
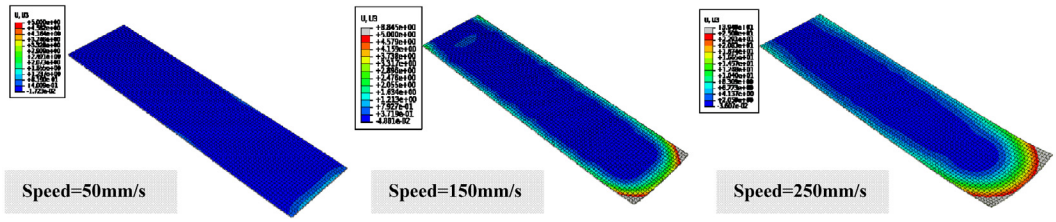
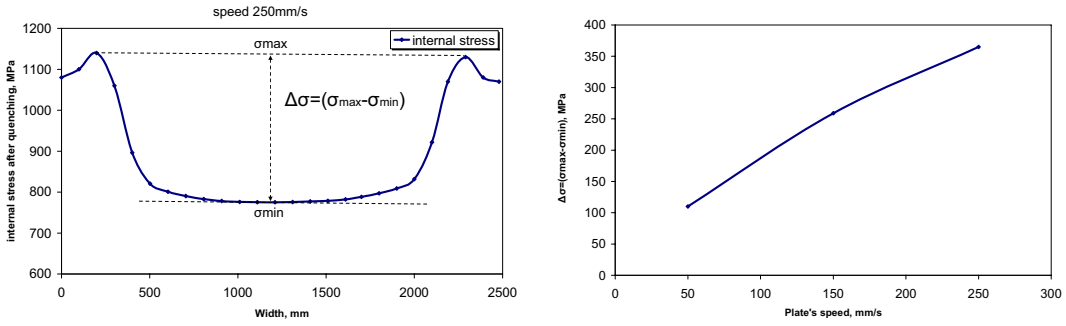


Fig. 7. Vertical displacement.

Fig. 7. Déplacement vertical.



(a)



(b)

Fig. 8. (a) Illustration of shape defects after quenching with different plate speed. (b) Stress analysis at quench exit.

Fig. 8. (a) Illustration des défauts de profil après trempe, pour différentes vitesses de la tôle. (b) Analyse des contraintes à la sortie de la trempe.

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Table 2. Cooling rate at top and mid surface of the plate.
Tableau 2. Vitesse de refroidissement en face supérieure et à mi-épaisseur de la tôle.

Thickness = 50 mm T = 900 °C uniform	Simulated cases	plate speed (mm/s)	Cooling rates at top surface (°C/s)	Cooling rates at middle surface (°C/s)
Effect of plate speed (mm/s)	Case n°1	50	–143	–16
	Case n°2	150	–258	
	Case n°3	250	–387	

the room temperature [4]. The difference of stress $\Delta\sigma$ between the edge and the center of the plate increases when the plate's speed increases and will create a more severe crossbow amplitude.

3 Thermal model and application in ArcelorMittal Burns Harbor quench

We developed a thermal model to compute the thermal evolution of the plate during the cooling in ArcelorMittal Burns Harbor quench. As flatness issues are related to the thermal gradient, the idea consists in determining cooling configurations necessary to achieve symmetrical thermal profile by adjusting the cooling parameters: top and bottom flow rates and speed of the plate [5].

Initial thermal condition is given by the exit furnace temperature. This temperature is assumed as constant and was verified by the experiments. The boundary conditions describe the different type of cooling met by the plate when it moves through the quench:

- Radiation and forced convection between the furnace and the cooling or after cooling.
- Water cooling in the High pressure zone $z1$ East Header.
- Water cooling in the High pressure zone $z2$ West Headers.
- Water cooling in the Low Pressure zone $z3$.
- Water cooling by stagnant water.

Figure 9a shows the interface of Burns Harbor quench model.

Simulations testing the effect of plate speed are done in order to analyze thermal gradient between top and bottom face during cooling. Results show that when the plate speed increase the thermal gradient increases also and becomes higher as illustrated in the Figure 9b.

The deflection during cooling mainly arises from unsymmetrical cooling in various directions. Based on thermal stresses and elasticity instability theory, the critical buckling stresses and type deflection due to uneven cooling thickness direction is given by Equation (1) [6]:

$$\sigma_C = \frac{KE\pi^2}{12(1-\nu^2)}\left(\frac{t}{W}\right)^2 \quad (1)$$

where t is the plate thickness, W is the width of the plate, v is Poisson's ratio of the steel, K the coefficient of buckling stress and E is the young modulus.

The thermal stress is given by Equation (2).

$$\sigma_T = E\alpha\Delta T \quad (2)$$

where α is the thermal expansion coefficient and ΔT is the temperature deviation in the thickness direction. Crossbow defects occur when the compressive thermal stress σT is greater than the critical buckling stress σc, Equation (3).

$$\sigma_T = E\alpha\Delta T \geq \frac{KE\pi^2}{12(1-\nu^2)}\left(\frac{t}{W}\right)^2 \quad (3)$$

The thermal stress depends strongly on the thermal gradient in the thickness direction. As we can see in the Figure 9b the thermal gradient for the plate speed 150 mm/s is about 40 °C and 150 °C for plate's speed 250 mm/s. When the thermal gradient increases the thermal stress increases and more severe crossbow are obtained. The goal of this model is to adjust quench parameters in term of speed and water flow in order to achieve more uniform cooling by reducing highly thermal heterogeneity.

4 Flatness measurement at Quench exit

A plate flatness measurement device has been developed by ArcelorMittal Global

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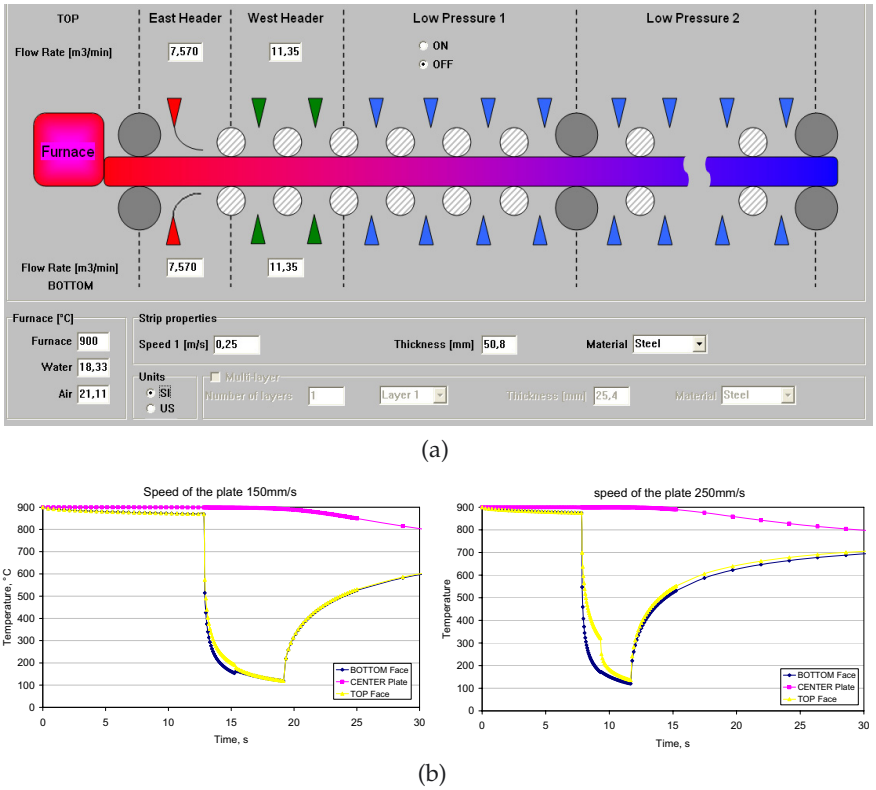


Fig. 9. (a) Burns Harbor quench model. (b) Illustration of the control of the dissymmetry of cooling by using BH quench model.

Fig. 9. (a) Le modèle de trempe de Burns Harbor. (b) Illustration de la maîtrise des dissymétries de refroidissement, par utilisation du modèle de trempe de Burns Harbor.

R&D and installed in the Burns Harbor heat treat facility. Tests including measurement of dry, wet, and hot plates are done to evaluate performance. Initial results show good measurement repeatability and performance.

This case of flatness measurement has been performed for a 25 mm thickness and shows a 3D view and global flatness of the plate after quenching (Fig. 10). The next step is to use this flatness measurement to control flatness at exit quench unit and to compare also the 3D distortions model and measurement.

5 Conclusion

The existing 3D thermo-mechanical model for quenching process is very useful to support industrial plant for the design of new quench investments and to improve the flatness issue in existing quench & temper device. It reproduced the different kind of flatness defects that are observed after plate quench treatment [1]. The model is also used to evaluate the effect of unsymmetrical cooling along various directions, the effect of non uniform temperature across the width and finally the effect of phase transformation austenite to martensite by a variation of thermal expansion.

Plate flatness is extremely sensitive to unsymmetrical cooling from top and bottom surface and the speed of the plate, which mean that very precise control of the speed and the flow rates set-point, are absolutely necessary.

Different tools to control flatness are developed by ArcelorMittal Global R&D and presented in this paper: 3D distortions model, Burns Harbor quench model and new flatness measurement. The current work at Burns Harbor quench unit is to link all these tools in order to optimize the quench process as much as possible.

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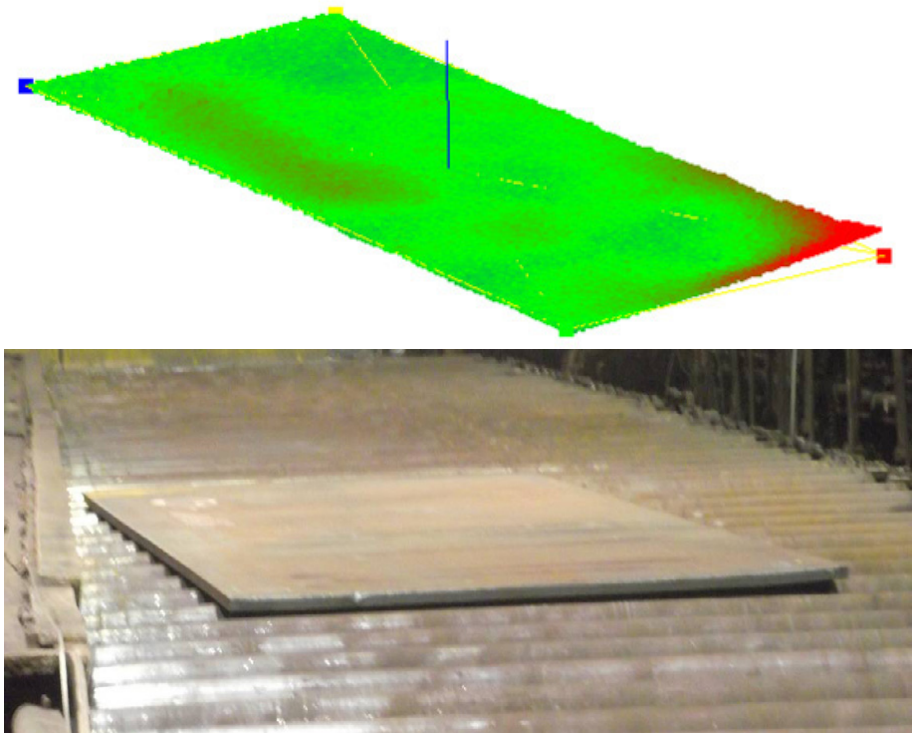


Fig. 10. Shape obtained by flatness measurement in comparison to the real shape of the plate.
Fig. 10. Comparaison entre le profil de la tôle obtenu par mesure de planéité et le profil réel.

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