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Determination of Cooling Practices for Cold Charging Crack-Sensitive Slabs at ArcelorMittal Plants

Stanovení postupů chlazení pro studené vsazování bram citlivých na trhliny v provozech ArcelorMittal

Chongzhi Abel Chang[1], Hongbin Yin[2]

[1] ArcelorMittal Global R&D Hamilton, Canada, 1390 Burlington Street East, Hamilton, Ontario, L8N 3J5, Canada, *Contact e-mail: abel.chang@arcelormittal.com

[2] ArcelorMittal Global R&D East Chicago, United States, 3001 East Columbus Dr., East Chicago IN 46312, United States, Contact e-mail: hongbin.yin@arcelormittal.com

Abstract

At conventional steel plants, some crack-sensitive slabs, such as high-alloyed AHSS (Advanced High-Strength Steel) and UHSS (Ultra-High-Strength Steel) grades, have to be cold charged due to restrictions associated with plant conditions. In order to minimize the risk of crack formation caused by thermal stresses during cooling, slow cooling must be applied to some of these slabs. To calculate the cooling stresses and temperature evolution, thermo-mechanical finite element (FE) models were developed. The results were analysed to estimate the risk of crack formation with the aim of determining the cooling practices for crack-sensitive slabs.

Keywords: *FE model, cold charging, crack formation, slow cooling, slab*

Abstrakt

V běžných ocelárnách musí být některé desky citlivé na praskání, například vysoce legované oceli AHSS (Advanced High-Strength Steel) a UHSS (Ultra-High-Strength Steel), podávány studeně kvůli omezením provozních podmínek. Aby se minimalizovalo riziko vzniku trhlin způsobených tepelným namáháním během ochlazování, je u některých z těchto desek nutné aplikovat pomalé ochlazování. Pro výpočet ochlazovacích napětí a vývoje teploty byly vyvinuty termomechanické modely konečných prvků (FE). Výsledky byly analyzovány za účelem odhadu rizika tvorby trhlin s cílem optimalizovat postupy ochlazování bram citlivých na trhliny.

Klíčová slova: *model konečných prvků (FE), studené sázení, bramy, pomalé ochlazování, tvorba trhlin*

1. Introduction

At conventional steel plants, steel slabs are delivered from the caster to the slab yard and stacked in a pile for cooling. This process is referred to as “normal stack cooling” (**Fig. 1a**). These slabs are either allowed to cool to ambient temperature and be subsequently charged into the reheating furnace (RHF), known as “cold charged” slabs, or they are moved directly to the RHF to be charged as hot as possible, termed “warm” or “hot” charging. In addition to significant energy and productivity benefits, warm charging is also able to reduce the risk of crack formation for crack-sensitive slabs that have high alloying elements.

At some ArcelorMittal plants, some crack-sensitive slabs (e.g., AHSS and UHSS grades) that are normal stack cooled and then cold charged can develop cracks caused by thermal stress. However, warm charging is not always available in these plants. Therefore, to reduce thermal stresses during cooling, these slabs must be cooled in an insulated cover (**Fig. 1b**) to ensure a very low cooling rate compared with normal stack cooling.

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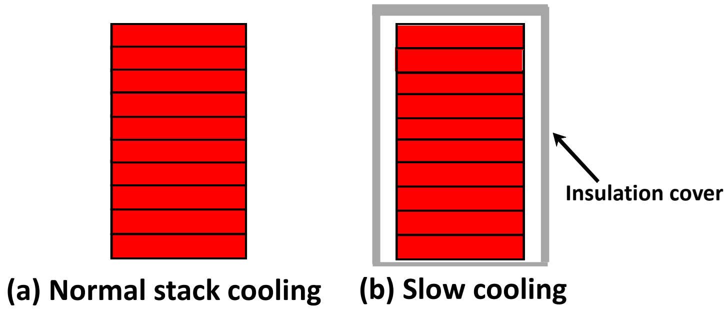

Fig. 1 Illustration of (a) normal stack cooling and (b) slow cooling

Obr. 1 Ilustrace (a) normálního chlazení a (b) pomalého chlazení

The slabs are then cold charged to the RHF of the hot mill. This cooling process is known as "slow cooling". Due to limitations in logistics, the number of insulated boxes, and productivity, it is difficult and uneconomical to slow cool all crack-sensitive grades.

In order to define the cooling practices for the crack-sensitive grades - in other words, to determine whether it is necessary to slow cool these slabs - finite element (FE) models were developed to simulate both slow and normal stack cooling processes, and the models were validated based on actual temperature measurements. The simulation results were used to characterize the risk of crack formation during cooling with the goal of defining the slab cooling practices at ArcelorMittal plants.

2. Methodology

The slab cooling models were developed using ABAQUS and consisted of two parts: thermal models and a stress model.

Thermal models (Normal stack cooling and Slow cooling)

Simulations were run to obtain the slab temperature evolutions for normal stack cooling and slow cooling. The slow cooling model was developed based on the previously developed normal stack cooling model. As shown in **Fig. 2**, the results reveal that the slow cooling slab takes a much longer time to reach the same temperature as the normal stack cooled slab. To allow for a valid comparison, these two simulations used the same initial conditions, slab dimensions, and grades.

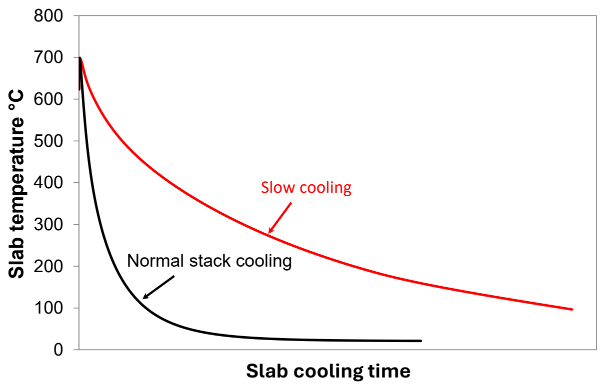

Fig. 2 Temperature evolutions during normal stack cooling and slow cooling processes

Obr. 2 Vývoj teploty během běžného a pomalého ochlazování

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Stress model

Temperature field data from the 3D thermal models is mapped to model the stress distribution developed during cooling as shown in **Fig. 3**. Simulation results of the stress models are applied to analyse stress evolution during normal stack cooling and slow cooling practices. Stresses induced by phase transformation inside slab is also considered in the simulation.

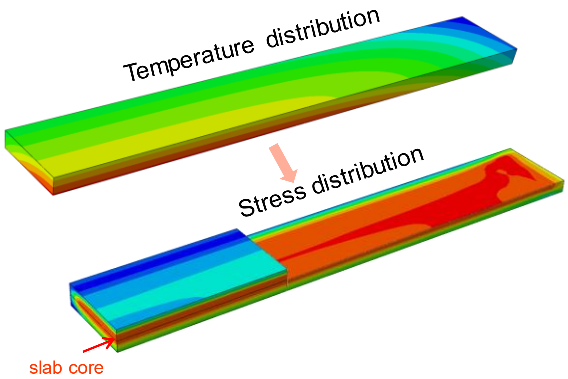

Fig. 3 Stress distribution of a slab during late-stage of cooling (Quarter-slab model)

Obr. 3 Distribuce napětí bramy v pozdní fázi ochlazování (Quarter-slab model)

Fig. 4 shows the stress evolutions of a crack-sensitive grade slab during normal stack cooling and slow cooling. The results indicate that the stresses in normal stack cooling are significantly higher than those in slow cooling after the early stage of cooling (slab temperature below approximately 500°C). In order to eliminate unnecessary variation, this study focuses on the stress analyses after this early stage of cooling.

In addition, it should be noted that stress alone is not sufficient to characterize the risk of crack formation if the effects of slab properties and temperature are not considered. Therefore, a crack formation index, which accounts for the effects of these factors and is calculated using an ABAQUS subroutine, is introduced and used to assess the risk of crack formation during cooling.

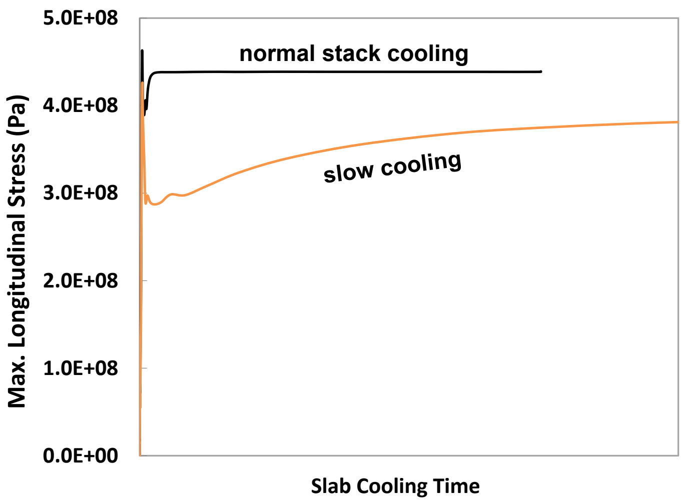

Fig. 4 Slab stress evolutions of a studied grade at various cooling conditions

Obr. 4 Vývoj napětí bramy u zkoumaného druhu oceli za různých podmínek ochlazování

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Input and output of the models

The inputs and outputs of the FE models are shown in **Fig. 5**. The thermal properties and phase transformation temperatures for different steel grades were measured in the lab, calculated with commercial software or obtained from literature data [1]. The mechanical properties of the studied cracking sensitive grades were measured on as-cast slabs.

Since mechanical property test samples were taken from different positions along the cross-section of the slabs, the variation in mechanical properties was also considered in this study. The models were applied to both slab cooling and reheating processes [1]. However, this study focuses on the analysis of slab cooling processes.

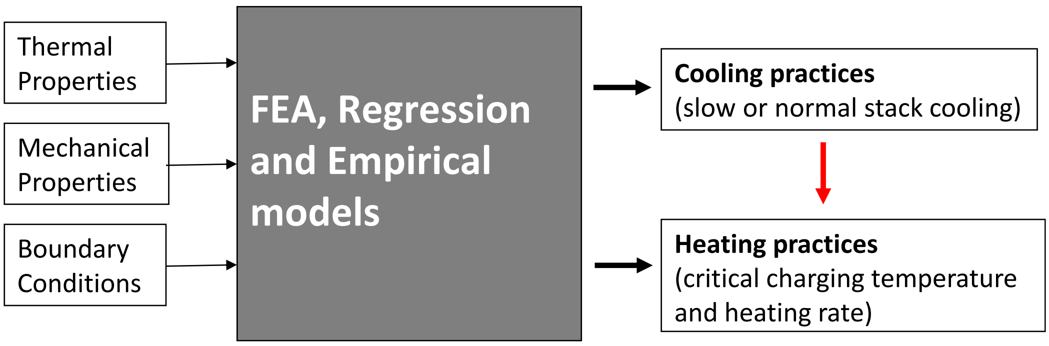

Fig. 5 Inputs and outputs of the models

Obr. 5 Vstupy a výstupy modelů

3. Results Analysis

Slab stress and temperature are calculated using the FE models. Based on the analysis of simulation results and historical data on slab cracking and breakage incidents, cooling practices are proposed.

Crack formation index - Characterizing the risk of crack formation

Simulations were run to analyse the stress evolution of various crack-sensitive grades during slow cooling. As shown in **Fig. 6**, after the early stage of slab cooling, the stress of slab Grade A is the lowest and Grade D slab is the highest among the studied grades during slow cooling.

As mentioned earlier, to better characterizing the risks of crack initiation and propagation caused by thermal stress, crack formation index can be obtained based on stress evolution after early stage of cooling.

The results plotted in **Fig. 7** show that, for all crack-sensitive grades subjected to slow cooling until reaching ambient temperature, Grade B has the highest crack formation index, and Grade A has the lowest, representing the highest and lowest risk of cracking, respectively, among the studied grades.

As shown in **Fig. 6**, the sequence of slow cooling stress for the studied grades, from highest to lowest, is D, B, C, A. This differs from the sequence of crack formation index: B, C, D, A. These results demonstrate that crack formation index should be employed to analyse the risk of crack formation.

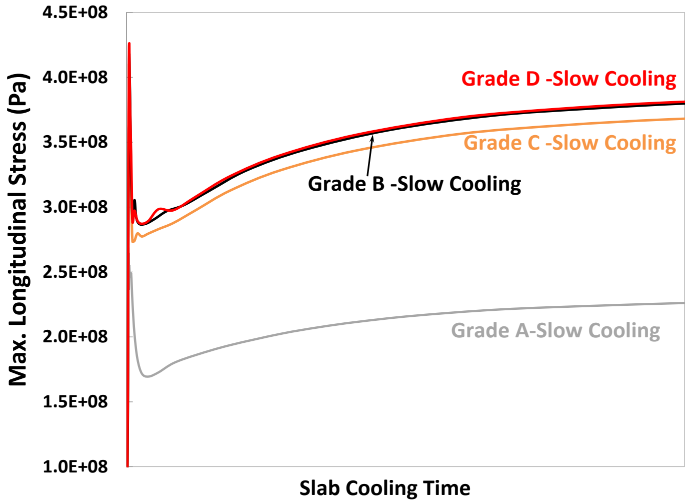

Fig. 6 Slow cooling stress evolution of various studied grades

Obr. 6 Vývoj napětí při pomalém ochlazování u různých zkoumaných jakostí

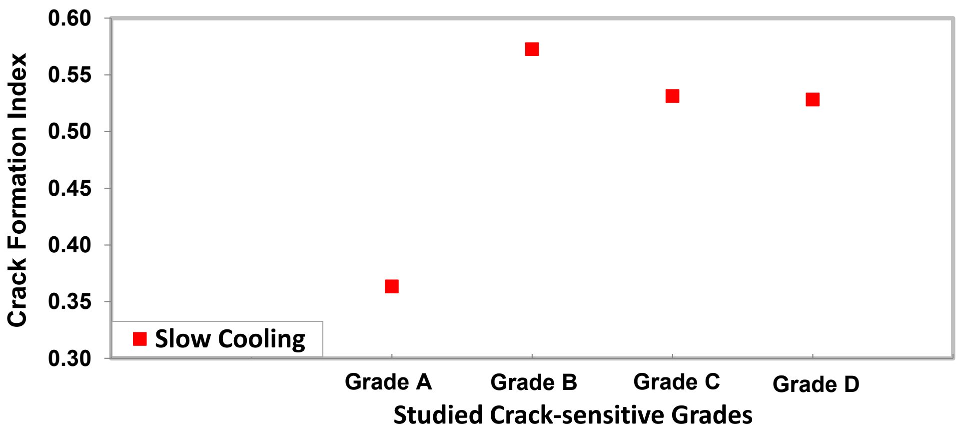

Fig. 7 Crack formation index of different crack-sensitive grades during slow cooling

Obr. 7 Index tvorby trhlin u různých druhů oceli náchylných k tvorbě trhlin při pomalém ochlazování

Determine the cooling practice based on crack formation index and historical data

To estimate the risk of crack formation, in addition to the crack formation index of slow cooled slabs, the analysis also considered the crack formation index of normal stack cooled slabs, historical production data of crack-sensitive grades, and reference grades.

Fig. 8 displays the crack formation index of each studied grade during both normal stack cooling and slow cooling. Grade E, which has relatively high alloying elements, is included as a reference because it has undergone normal stack cooling and cold charging for many years at some ArcelorMittal plants without any defects caused by thermal stresses. As shown in **Fig. 8**, the crack formation index of normal stack cooled Grade A slabs is lower than that of Grade E slabs.

Therefore, slow cooling Grade A is not necessary. The crack formation index of Grade E during normal stack cooling is significantly lower than those of Grade B, C and D during slow cooling. This indicates that slow cooling Grade B, C and D slabs have higher risk of crack formation than normal stack cooling of Grade E, so further analyses is required to define their cooling practices.

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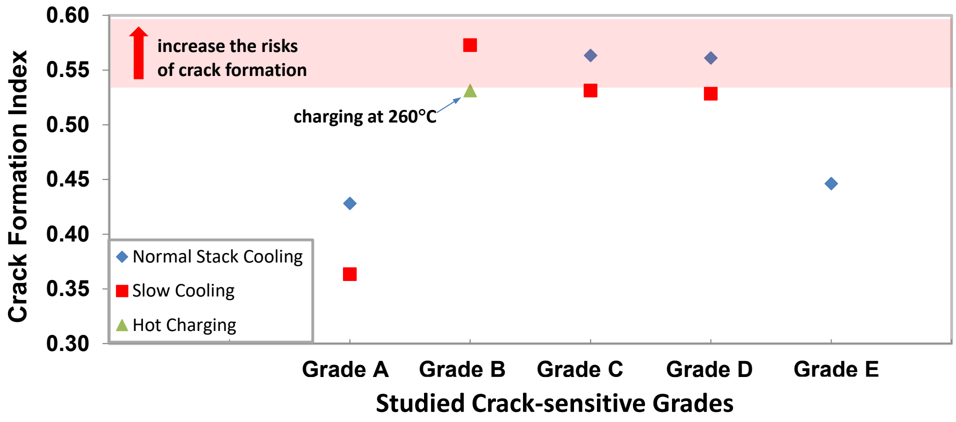

Fig. 8 Crack formation index of different crack-sensitive grades during normal stack cooling and slow cooling

Obr. 8 Index tvorby trhlin u různých druhů oceli náchylných k tvorbě trhlin při běžném ochlazování a při pomalém ochlazování

In trials at ArcelorMittal plants, cracks were found on the normal stack cooled Grade D slabs and the slow cooled Grade B slabs, demonstrating that slow cooling is insufficient to lower the risk of crack formation for Grade B slabs. As shown in **Fig. 8**, the crack formation index of normal stack cooled Grade C and D is similar to that of slow cooled Grade B slabs, aligning with trial results. This, indicates that the Grade C and D slabs must be slow cooled.

Notably, cracks were not found on slow cooled and cold charged Grade C and D in the following trials. Thus, in terms of the simulation results and actual industrial trials, slow cooled and cold charged Grade C and D slabs can be considered as low risk of crack formation from the perspective of cooling stress analysis.

In addition, assuming that crack formation index of slow cooled Grade C is used as the critical index, simulation results suggest that slow cooling Grade B slabs should be charged with a temperature at least 260 °C to minimize cracking risk. However, this also means Grade B cannot be produced at plants where warm charging is unavailable.

The proposed cooling practices of the studied grades are summarized in **Tab. 1**. They have been successfully implemented at several ArcelorMittal plants for over five years. This method is also applied to determine cooling practices for newly developed crack-sensitive grades, as well as to optimize reheating practices for both newly developed and historical crack-sensitive grades.

Tab. 1 Summary of cooling practices of the studied crack sensitive slabs
Tab. 1 Přehled způsobů chlazení zkoumaných desek náchylných ke vzniku trhlin

Studied grades	Slow cooling	Cold charging
Grade A	No	Yes
Grade B	Yes	No (require warm charging)
Grade C	Yes	Yes
Grade D	Yes	Yes
Grade E	No	Yes

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It should be noted that this study focuses on cooling stress analysis. In addition to the cooling stress and temperature, slab microstructure, heating rate, martensite formation, hydrogen embrittlement and abnormal process parameters also play important roles in crack formation.

4. Summary and Conclusions

Thermo-mechanical FE models were successfully developed to simulate normal stack cooling and slow cooling processes of slabs under plant-specific conditions. In order to characterize the risk of crack formation, the concept of crack formation index was introduced.

Based on the crack formation index and historical data from production trials of the studied crack-sensitive grades, cooling and charging practices can be determined for various grades. These proposed cooling practices can significantly reduce the risk of crack formation for these grades.

These practices have been successfully implemented for more than five years at several ArcelorMittal plants which produce highly crack-sensitive grades. The methodology is also used to determine cooling practices for newly developed crack-sensitive grades, as well as reheating practices at hot mills.

This report focuses on cooling stress analysis. Other factors, such as slab microstructure, heating rate, martensite formation, hydrogen embrittlement and abnormal process parameters, can also significantly affect the risk of crack formation.

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Reference

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