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Heat transfer analysis of hot-rolled coils in multi-stack storing

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Abstract

Steel strip coil is the final product of the hot-rolling process. A model for cooling in hot-rolled coils is presented. Several important factors such as coiling temperature, oxidized layer thickness, pressure between different layers of a coil and varying ambient temperature are considered in the model. A computer code based on the model is developed. Satisfactory agreement between experimental and computational results confirms the accuracy of the model. Effects of some factors such as coiling temperature and ambient temperature on required cooling time of both single and multi-stack storing of coils are presented.

Keywords: Heat transfer; Multi-stack storing; Hot-rolled coil

1. Introduction

Steel strip coil is the final product of the hot-rolling process. Hot rolled strips are coiled at 550–750 °C. Before the coils can be sent to pickling line or supplied to the market they must be cooled to ambient temperature (∼40 °C). Depending on the size of coils natural cooling can take 6–9 days, which leads to an increase in storage space and lengthen production cycle.

A mathematical model capable of predicting the cooling behavior of coils would have the advantage of being used to develop a suitable method to reduce the cooling time. This is achieved by investigating the effects of different factors such as coiling temperature, ambient temperature, cooling method and storing attitude on the cooling time at very slim additional cost or time.

A number of studies have been carried out on the coil cooling behavior. Gasho et al. [1] studied the cooling behavior of coils under steady conditions and obtained a logarithmic relation for the cooling rate of coils. Mazur et al. [2] studied the defects occurring in coils during storage time and compared the cooling behavior of coils for vertical and horizontal attitude. In another study, Mazur et al. [3] developed a simple mathematical model that could be used to study forced rapid cooling methods and investigated water spray and immersion cooling methods. To optimize steel coil cooling times Baik and co-workers [4,5] solved the heat transfer equation using the finite element method and compared the computational results for different methods of cooling with experimental data [4,5]. To develop an automated storage of coils from the hot rolling process, Horst [6] have developed a simulator to examine the effects of various factors involved in cooling time of a coil such as coiling temperature, coil weight and dimensions, as well as the effects of surrounding conditions.

The above studies have all examined the cooling behavior of coils in the single-stack attitude. Given the real storing conditions in the Mobarakeh Steel Complex where coils are vertically stack up, the present study seeks to investigate the cooling of multi-stack coils in addition to the single-stack one. This study also compares the results obtained from the numerical simulation of the problem with real measurements reported from the coils in the storehouse. Furthers, the effects of a number of factors such as coiling temperature and ambient temperature on the cooling behavior of both single and multi-stack coils are presented.

2. The heat transfer model

Due to coil shape and symmetry, it suffices to consider the two dimensional heat transfer conduction equation in cylindrical

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Nomenclature

A	ratio of actual contact area to apparent contact area
C	specific heat (J/kg °C)
E	module of elasticity (MPa)
H	micro-hardness (MPa)
k	thermal conductivity (W/m °C)
m	effective mean absolute surface slope (rad)
P	pressure (MPa)
R	thermal resistance (m^2 °C/W)
r	radius of coil at different location (m)
S	Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
t	thickness (m)
T	temperature (K, °C)
ε	emission coefficient
λ	thermal expansion (°C^{-1})
ρ	density (kg/m^3)
σ_p	standard deviation of profile height for asperity
τ	time (s)

Subscripts

a	air
cd	conduction
coil	coiling
i	intermediate
o	oxide
rd	radiation
r	radial
s	steel
z	axial

coordinates (Eq. (1)):

$$\frac{\partial}{\partial \tau}(\rho c T) = \frac{1}{r}\frac{\partial}{\partial r}\left(k_r r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) \tag{1}$$

Changes in steel physical properties such as thermal conductivity and specific heat resulting from large temperature variations during the cooling time must be accounted for. The most important term of Eq. (1) is the heat conduction along the radial direction. Many layers of steel strip are stacked on each other in a coil (Fig. 1). The heat transfer within the oxidized layer of the steel strip and the intermediate layer forming the contact surface between two adjacent strips must be considered when calculating the equivalent thermal conductivity along the radial direction. Heat resistances of the strip layer and the oxide layer can be calculated from the following relations:

$$R_s = \frac{t_s}{k_s} \tag{2}$$

$$R_o = \frac{t_o}{k_o} \tag{3}$$

The thickness of the iron oxide on the steel strips can be measured from the reduced weight during pickling and is approximately 10 μm for various strip thicknesses. Thermal conductivity of iron oxide does not vary considerably with temperature and is to be 2.3 W/m °C [7].

The intermediate layer plays a great role in radial thermal conductivity. Two seemingly flat surfaces come into contact only at certain points when they are in contact with each other as explained by their asperity. Between contact points, air cavities exist. Thus, the intermediate layer transfer heat in three ways:

a. conduction at contact points, $R_{cd,s}$;
b. conduction by the air confined within cavities, $R_{cd,a}$;
c. radiation within the cavities, R_{rd}.

And the equivalent thermal conductivity is

$$k_r = \frac{t}{R_s + R_o + 1/((1/R_{cd,s}) + (1/R_{cd,a}) + (1/R_{rd}))} \tag{4}$$

where t is the sum of thicknesses of the steel, the oxide layer, and the intermediate layer.

An essential parameter that must be known in order to determine the thermal resistance of the intermediate layer is the ratio of the actual contact area (sum of contact points area) to the apparent contact area. It must be noted that this ratio (A) itself is a function of physical properties of the two surfaces in contact and of the vertical pressure between them [8]. A variety of relations have been proposed to explain the above interdependence [9]. Among these, Pullen and Williamson [10] obtained the fol-

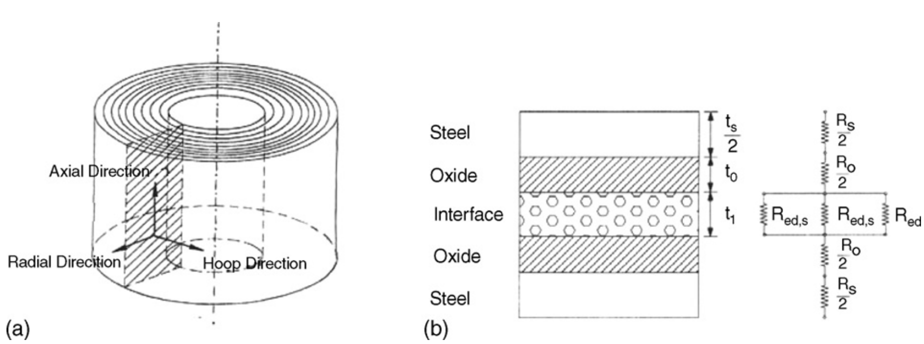

Fig. 1. (a) Cross-section of hot-roll coil; (b) thermal resistance of steel, oxide and intermediate layers in radial direction.