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Effects of the residual stress, interfacial roughness and scale thickness on the spallation of oxide scale grown on hot rolled steel sheet

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ABSTRACT

Failure at the interface between a steel substrate and oxide scale was investigated by semi-analytical and finite element numerical simulations. Two major stress components along the interface, i.e., tensile normal stress at the peak and shear stress at the inflection point of the idealized undulated interface, were calculated and used for the failure analysis. The mechanical properties of the oxide scale and steel substrate were experimentally measured by the indentation and uniaxial tensile tests, respectively. Growth and thermal residual stresses accumulated at the oxide scale during cooling were calculated by a coupled numerical-analytical method, which was experimentally validated by measuring the residual stresses in the oxide scales with different thicknesses. The finite element simulation of a four-point bending test was conducted in order to reproduce uncoiling process during which spallation of oxide scale may occur. From the analysis of the simulation results, the two major stress components turned out to be amplified by the roughness of the interface and the residual stresses generated by the growth stress of oxide scale and the thermal mismatch between the oxide and steel substrate during cooling. In addition, the shear stress proved to be a significant factor for the spallation behavior. The effect of scale thickness on the spallation was discussed by using the concept of failure map based on interfacial fracture energy.

1. Introduction

Hot rolling is a typical process to produce metal plates and sheets, in which the thickness varies depending on the rolling design such as number of rollers and roll gaps [1]. The hot rolling process consists of furnace heating, primary descaling, roughing mills, secondary descaling, finishing mills and run out table (ROT) as schematically illustrated in Fig. 1. Right after passing the reheating furnace, the material is in the range of temperature from 1000 to 1100 °C. The consecutive milling process reduces the temperature to the range from 800 to 900 °C at the exit of finishing mills. The ROT makes the strip rapidly cooled down the temperature ranging from 500 to 750 °C, which is followed by coiling process and the coiled strip becomes cooled in the air for 2 or 3 days [1–4].

When the sheet starts to leave the finishing mills, oxide scale grows on the surface of carbon steel. The oxide scale is typically composed of three layers: hematite (Fe_2O_3) at the outer surface, magnetite (Fe_3O_4) at the intermediate region, and wüstite (FeO) at the inner region close to the interface. Magnetite phase dominates at room temperature because unstable wüstite phase transforms to magnetite phase below 570 °C [5,6]. The cooling rate, heat-treatment temperature, and exposure time are major factors influencing the growth and structure of the oxide scale.

In the production of high-quality hot rolled products, descaling process is essential to remove oxide scale grown on the surface of a steel strip. Before entering the roughing mills, the strip passes through the primary descaling zone for the removal of the oxide scale formed at the surface of the steel in the oxygen-rich atmosphere. The secondary oxide scale continuously grows on the retained oxide scale and reaches the thickness ranging from 20 to 100 µm while staying on the roughing mills [1]. This secondary descaling process imposes higher pressure on the scale because it is known to be stickier than the primary scale. Despite this secondary descaling process, the oxide scale accumulates additionally by experiencing the multiple passage of finishing mills. Consequently, the oxide scale gains the thickness ranging from 10 to 20 µm at the end of finishing mills [7]. This oxide scale still remains

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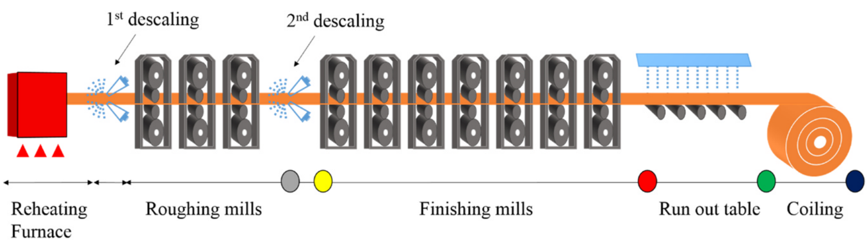

Fig. 1. Schematic of general hot rolling process.

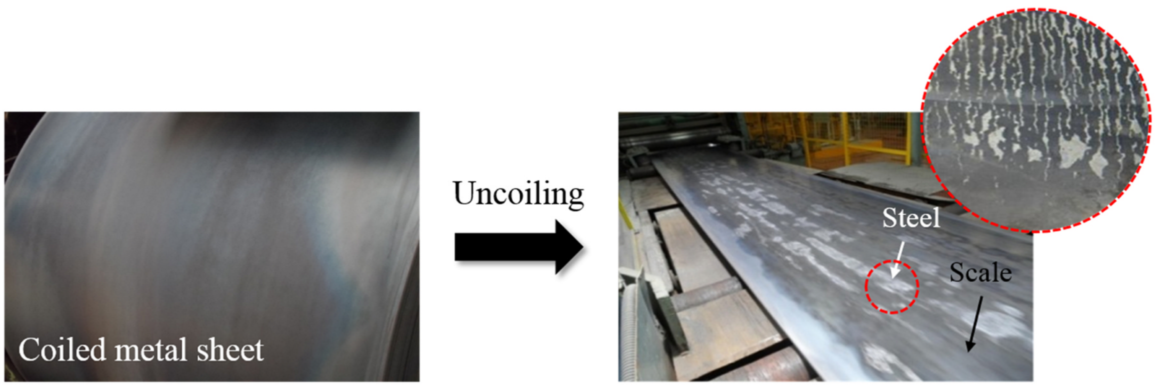

Fig. 2. Spallation of the oxide scale after uncoiling process.

after end of coiling process and prevents corrosion of the surface as a positive effect. When the sheet metal is subject to external loadings such as uncoiling process prior to sheet forming operation, meanwhile, unexpected spallation has been often observed as shown in Fig. 2, which might result from interface debonding between the metal substrate and the oxide scale. There are several factors influencing oxide scale spallation during uncoiling. These include residual stress developed during the hot rolling process, scale thickness, interface geometry, bending curvature of coil, porosity in the oxide scale layer, and initial crack at the interface. Previous studies [8–11] introduced the failure criteria under tensile and compressive stresses induced by the mismatch of the thermal property and deformation with scale cracks by pre-existing flaws. The effect of normal stress at the interface of thermal barrier coating [12,13] and mild steel surface [14] was investigated by numerical simulations.

The present study aims to examine the mechanism of oxide scale spallation occurred during uncoiling. The analysis was motivated by the presumption that the geometrical feature of the interface between oxide scale and steel substrate plays a major role in inducing stress on the interface [14]. The general interfacial stress state including shear component was considered as potential mechanism of the spallation, unlike the previous research involving normal stress only [15]. As for a hot rolled low-carbon steel, the mechanical properties of the oxide scale and steel substrate were experimentally measured by the indentation and uniaxial tensile tests, respectively. With consideration of scale growth and thermal mismatch during hot rolling process, residual stress of the coiled strip was also calculated by a coupled numerical-analytical method. The finite element simulation of a four-point bending test was conducted in order to reproduce uncoiling process during which spallation of oxide scale may occur. For efficient analysis, the actual interfacial geometry was simplified as a periodic undulation showing amplitude and period as schematically depicted in Fig. 3. An intensive numerical sensitivity study is provided by variance of interfacial geometric parameters such as interface undulation and the scale thickness. Three spots at the interface shown in Fig. 3; i.e., the peak, valley, and inflection regions, was considered as potential fracture spots and their stresses were analyzed to clarify spallation mechanism of the oxide scale. An intensive numerical sensitivity study is also provided by

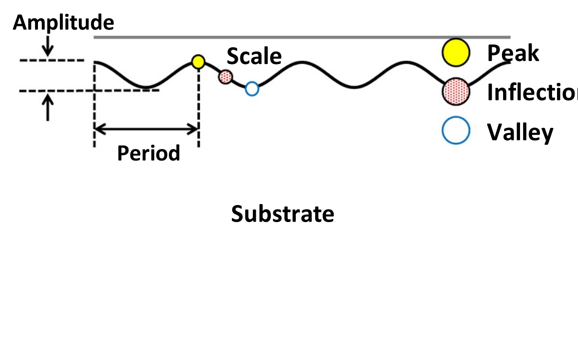

Fig. 3. Geometrical dimensions of the idealized interface between oxide scale and steel substrate and three characteristic locations of interest.

applying the cohesive zone brittle fracture model in ABAQUS finite element software [12,16,17].

This paper is organized as following. In Section 2, the existing observation of the oxide scale fracture and associated fracture models are summarized. In Section 3, experimental procedures for identifying the mechanical and thermal properties of oxide scale and steel substrate are presented. Moreover, there is a methodology presented for measuring the residual stresses accumulated in the oxide scales with different thicknesses. In Section 4, the newly proposed numerical approach for the calculation of residual stress in the oxide scale and finite element model for the analysis of interfacial spallation are presented. The detailed sensitivity analyses and discussions are followed in the Section 5.

2. Summary of fracture mechanism of the oxide scale-metal interface

Evans and Lobb [18] suggested that spallation at the oxide-metal interface is attributed to the thermal stress induced from the difference in coefficients of thermal expansion (CTE) between oxide scale and metal during change of temperature. They proposed three types of scale fracture schematically shown in Fig. 4, in which α denotes CTE with subscripts *sub* and *ox* for substrate and oxides scale, respectively. In the