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Spallation analysis of oxide scale on low carbon steel

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ABSTRACT

Failure at the interface between a steel substrate and the oxide scale was analyzed by finite element 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 undulated interface geometry, were calculated and used for the analysis. The mechanical properties of the oxide scale and steel substrate were experimentally measured by indentation and by uniaxial tensile tests, respectively. The simulations consist of cooling from 1000 °C to room temperature to predict residual stresses accumulated during cooling, followed by additional four-point bending to represent the uncoiling process. The two major stress components were amplified by the roughness of the interface and by the residual stress generated by thermal mismatch between the oxide and the steel substrate during cooling. In addition, the shear stress was proved to be a significant factor for the spallation behavior; this fact had not been well recognized in the previous literature. The finite element simulation showed that the severity of the fracture-inducing stress components increases as the oxide thickness and the period of the idealized undulation decrease; the severity also increases as the amplitude of the roughness increases.

1. Introduction

In the hot rolling process, oxide scale is inevitably grown on the material surface because of the nature of its high temperature deformation. Therefore, so-called descaling processes have been used to remove the unnecessary oxide scale. One of the typical ways for the descaling of oxide scale is the high-pressure water jet. In general, the hot rolling process consists of several regions, i.e., a primary descaling box, roughing mills, a secondary descaling box, finishing mills and a run-out table (ROT) for cooling the rolled material. During the ROT, the material is rapidly cooled down to 500–700 °C, followed by coiling and cooling to room temperature in the air for 2 or 3 days [1–4]. The oxide scale grows on the surface of the sheet during its passage through the rolls. The oxide scale grown on the low carbon steel substrate consists of multiple layers of hematite (Fe_2O_3), magnetite (Fe_3O_4) and wüstite (FeO) phases [2]. The three constituents of the oxide scale have different properties, and the fraction varies with heat-treatment time, cooling rate, and the ambient atmosphere [2,4,5].

To remove the primary scale formed at the outlet of the furnace, a slab passes through the descaling box before entering the roughing mills. Then, secondary oxide scale grows between continuous rolling passes, which should be removed by high-pressure water jets in the descaling box before entering the finishing mills. Despite the descaling process, however, additional oxide scale forms during the passage through successive finishing mills. This oxide scale remains after coiling, and—although it is minor compared to the thickness of the primary oxide scale removed in the prior rolling processes—it should remain firmly attached to the final product to prevent corrosion and to maintain the surface quality. However, as a result of external loading such as uncoiling of the sheet for metal forming operation, unexpected spallation (or interface debonding between the metal substrate and the oxide scale) has been frequently reported.

The usual thickness of the primary oxide scales ranges from 20 to 100 μm before passing into the descaling box, and decreases down to ~20 μm after the ROT [4]. The spallation or decohesion of the oxide scale in steels has been mainly regarded as a result of interfacial fracture at the interface between the oxide scale and the metal substrate. In addition, the interfacial fracture was accelerated by the microstructural-level destruction of the oxide scale due to prior existing porosities or initial cracks [5–9]. Previous investigations of the mechanism of spallation at the interface usually focused on the normal stress development at the interface by simple deformation such as bending of the sheet. That is, when the traction along the interfacial normal direction is beyond the fracture limit of the interface, spallation is assumed to occur. There are several factors influencing the fracture of the oxide scale at the interface; these include bending curvature during uncoiling, volume fraction and size of the porosity in the

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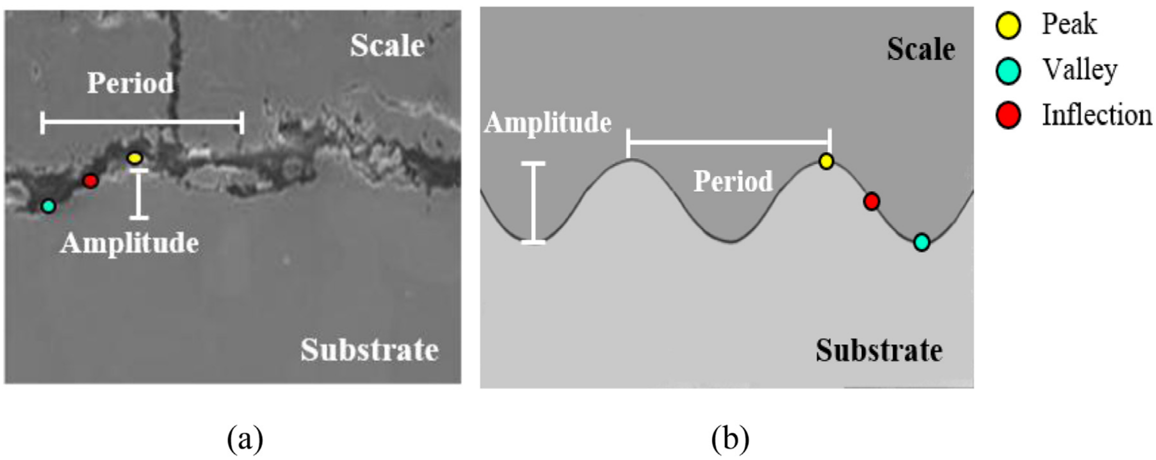

Fig. 1. Geometrical dimensions of the interface between the oxide scale and the steel substrate: (a) interface fracture along the interface, (b) simplified interfacial geometry and definitions for the three locations of interest.

oxide scale, initial crack size at the interface, residual stress developed during the hot rolling process, scale thickness, and the geometry of the interface.

The present study aims to examine the mechanism of oxide scale spallation during simple bending deformation. The analysis was motivated by the fact that the spallation is initiated by the interfacial stresses induced by the geometrical features of the interface between the oxide scale and the low carbon steel substrate. This is a reasonable presumption because the interfacial normal stress is very low in the case of a flat interface without any undulation during bending. However, in this study—unlike the previous researches—the general stress distribution including the shear component acting on the interface is also considered as a potential mechanism of the spallation. The role of shear stress component is particularly investigated considering the classical brittle failure model as a function of both normal and shear stress components on the fracture plane. For this purpose, finite element (FE) modeling was used by considering the variation of the interfacial dimensions such as roughness (or undulation) of the interface, and the scale thickness. For efficient analysis, the realistic interfacial geometry shown in Fig. 1(a) will be simplified as an undulation with constant amplitude and period as schematically drawn in Fig. 1(b). In the figure, three regions at the interface; i.e., the peak, valley, and inflection regions, represent critical spots for the potential fracture regions from the stress components developed during bending. Moreover, the effect of residual stress developed at the interface because of the mismatch of thermal expansions between the oxide scale and the metal substrate will be also investigated because this also influences the magnitude of major traction components at the interface [10]. An intensive numerical sensitivity study is provided by applying the cohesive zone brittle fracture model in ABAQUS finite element software [9,11,12]. To simplify the realistic uncoiling process, a four-point bending configuration is used for all the simulations.

2. Experiments

2.1. Model material

The material considered in this study is a low carbon steel sheet, on which an oxide scale was grown with a thickness of approximately 10–18 μm. The chemical composition of the low carbon steel substrate is 0.05C-0.7Mn-0.04Al-0.01Si-0.01P in weight %, and the average grain size was about 10 μm. The thickness of the substrate was 5 mm. The oxide scale mainly consisted of magnetite (Fe_3O_4) with a small fraction of hematite (Fe_2O_3) and wüstite (FeO) layers, depending on the thickness of the scale. Because the steel was slowly cooled down to room temperature in air, the majority of the magnetite layer was observed in the scale [2]. Examples of the oxide scale composition are shown in Table 1. The structure of the oxide scale was measured by X-ray diffraction.

Table 1
Composition of the oxide scale as a function of thickness after hot rolling.

Scale thickness (μm)	FeO (%)	Fe_3O_4 (%)	Fe_2O_3 (%)
10.3	–	94.6	5.4
16.5	10.7	89.3	–
18.0	10.3	89.4	–

Table 2
The flow stress curves of the low carbon steel fitted to combined Swift-Voce model.

	Plastic property, S-V model				
Temperature (°C)	***A*** **(MPa)**	$\bar{\varepsilon}_0$	***n***	***B*** **(MPa)**	*p*
25	559.6	$5.5e^{-4}$	0.21	22	32.0
100	552.6	$7.9e^{-3}$	0.23	44	17.9
200	288.5	$1.8e^{-1}$	0.20	286	21.0
300	406.9	$3.3e^{-2}$	0.27	221	30.1
400	463.6	$3.2e^{-3}$	0.20	90	34.2
500	349.9	$4.8\ e^{-3}$	0.16	25	68.7
600	162.6	$9.7e^{-4}$	0.05	21	33.5
700	88.2	$4.2e^{-3}$	0.04	6	742
800	52.6	$4.5\ e^{-1}$	0.27	4	777
900	66.2	$5.0e^{-3}$	0.07	8	39.7

* Poisson's ratio was assumed as 0.3 for whole temperature range

2.2. Mechanical properties of steel substrate and oxide scale

In this study, the oxide scale was assumed to behave as an elastic material, while the substrate exhibits elastic-plastic behavior. Both elastic and plastic properties were assumed as rate insensitive. These mechanical properties will be applied to the finite-element analysis described in the next section. The elastic and plastic properties of the low carbon steel substrate were measured by a uniaxial tensile test from room temperature to 900 °C with a crosshead speed of 1 mm/min, and are listed in Table 2. The plastic properties of the substrate were fitted by the Swift-Voce (S-V) combined type hardening law as follows: