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Formation mechanism of surface scale defects in hot rolling process

Hiroshi Utsunomiya (2)[a,*], Kenichiro Hara[a], Ryo Matsumoto[a], Akira Azushima (1)[b]

[a] Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan
[b] Department of Mechanical Engineering, Graduate School of Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogya-ku, Yokohama 240-8501, Japan

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ABSTRACT

Thick oxide scale on steel may result in serious surface defects on hot-worked products. Yield efficiency and productivity of processes are considerably deteriorated by formation of defects. It is highly demanded to establish a way to produce hot-worked steels free from surface defects by controlling oxide scale. The oxide scale shows various behaviors in hot rolling; (a) uniform deformation with matrix steel, (b) cracking, (c) fragmentation, (d) indentation to matrix steel, etc. Through observations using glass coating, it is found that the behavior strongly depends on the rolling temperature as well as the scale thickness before rolling. Temperature drop due to contact with cold rolls is found to cause the cracking and a major reason for the thickness dependence. It is found that the scale cracking is predictable using the estimated scale temperature and the ductile-brittle transition temperature of Wustite (FeO). Then, methodology to produce hot rolled steels without surface defects in industrial processes is presented.

1. Introduction

In industrial hot working of steels and other alloys, it is always important to improve productivity and yield efficiency of processes. Better dimensional accuracy, surface quality, microstructure and properties of products are also demanded. As the oxide scale formed on the workpiece could be a cause of these problems, it is highly preferable to establish a way to control the scale behavior [1]. Mechanical and water-jet descalers are often used in steel plants to make the scale subjected to hot working sufficiently thin and to improve surface quality. However, frequent descaling increases scale loss and decreases yield efficiency. It takes more machines and electricity. It is not easy to design the specifications and position of descalers in steel plants. In this paper, the authors propose a method to predict formation of scale defects in steel hot rolling. As an application, a technique to produce sheets free from scale defects in industrial processes with consideration of scale behavior is also presented.

Although high-temperature oxidation phenomenon has been studied widely by chemists and metallurgists, the behavior of the scale during hot-working has not been made clear sufficiently. This is because *in situ* observation is difficult due to high-temperature and high-speed nature of hot working. In addition, the scale starts to grow in atmosphere even after the hot working. In order to avoid the secondary oxidation, Okada [2] and Sun et al. [3] used cooling chambers filled with nitrogen to observe the as hot-rolled scale on the steel sheet. On the other hand, the authors proposed to coat the steel surface immediately after hot rolling using oxide glass [4]. The deformation behavior of oxide scale on low carbon steel and the influence on rolling characteristics were studied under several hot-rolling conditions. In addition, it was found that thick scale decreases friction coefficient by non-uniform scale deformation and decreases the heat transfer from the hot steel to the cold rolls [5].

Through these experiments, it was made clear that the scale shows various complicated behaviors during hot rolling; (a) uniform deformation with matrix steel, (b) cracking, (c) fragmentation, (d) indentation to matrix steel, etc. It is notable that the scale is not always brittle but shows some ductility depending on hot rolling conditions. Lenard reported that the behavior depends on the temperature as well as the scale thickness [6]. As the ductility of the oxide scale increases remarkably with increasing temperature in tensile test [7], the deformation of scale in hot rolling may be affected by the real surface temperature in the roll bite.

In this study, hot rolling experiments were conducted to investigate the scale deformation including the thickness dependence in detail. Through the observations, the complicated scale deformations were classified based on morphologies after the rolling. Then, the scale deformation was predicted with the scale temperature estimated by simple thermal analysis. Using reported properties of Wustite (FeO) at high temperature, fracture conditions of the scale which can account for the experimental behaviors are proposed. Using the conditions, methodology to avoid scale defects in industrial hot rolling processes is derived.

2. Deformation of oxide scale during hot rolling

2.1. Oxidation and rolling experiment

Low carbon steel (0.17% C–0.01% Si–0.46% Mn–0.01% P–0.007% S) sheets were received. The dimensions were 3.2 mm thick, 25 mm wide and 300 mm long. Experimental apparatus used is schematically shown in Fig. 1. The pickled sheet was inserted to a tube furnace at hot rolling temperature (T = 1173 K, 1273 K, 1373 K) filled

* Corresponding author.

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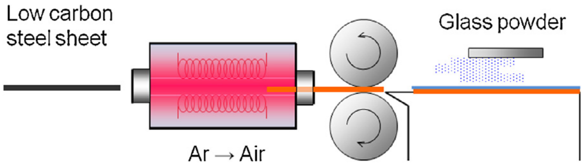

Fig. 1. Schematic illustration of hot rolling experiments.

with argon. After heating for 900 s, argon was substituted by air to allow oxide scale to grow for t = 0 s (without intended duration) or 40 s. Then, the sheets were immediately rolled on a rolling mill with rolls 100 mm in diameter. The sheet thickness was reduced 30% by one-pass operation at 300 mm/s without lubrication. After the sheet passing the roll gap, glass powder was sprinkled over the sheet for glass coating. Longitudinal sections (TD plane) were observed with a scanning electron microscope (SEM).

2.2. Morphology of oxide scale after rolling

The scale grew even in the case without intended oxidation time (t = 0 s) because the sheet was oxidized slightly when the sheet was inserted and taken out from the furnace. Without intended oxidation duration (t = 0 s), the scale thickness was 2.4 μm, 2.7 μm and 8.1 μm at 1173 K, 1273 K and 1373 K, respectively. After 40 s of oxidation, the thickness was 32 μm, 33 μm and 43 μm at 1173 K, 1273 K and 1373 K, respectively.

Longitudinal sections of the sheets after the rolling are compared in Fig. 2. Without intended oxidation duration (t = 0 s), the scale was deformed uniformly without cracks or fractures at all the temperatures as seen in the left column of the figure. It means that the thin scale has sufficient ductility to follow the bulk plastic deformation of the matrix steel. When the oxidation duration was 40 s, at 1173 K, the scale was fragmented and was indented to the matrix steel periodically. The interface between the scale and the steel was wavy as seen in the figure. After t = 40 s at 1273 K, the scale deformed into wedge shape and was indented to the matrix steel. The matrix steel was extruded through the scale cracks to the outermost surface. At 1373 K, the scale had V-shaped cracks; however the interface between the scale and the steel were relatively smooth. It is confirmed that the scale deformation is sensitive to temperature as well as its thickness.

It is known that Wustite (FeO), the major component of the scale, shows plasticity at high temperature due to NaCl-type crystal structure. The scale is harder than the steel below 1273 K, while the scale is softer above 1373 K. The morphology of the thick scale after rolling can be explained by the difference in flow stress [8]. At 1173 K, hard brittle oxide was fragmented and indented to the matrix steel so that the interface was rough. On the other hand, at 1373 K, soft ductile scale was cracked on the hard steel so that the interface was relatively smooth. At 1273 K, limited ductility of scale results in edge-shaped morphology with an elongated thin end.

2.3. Classification of scale morphology after rolling

Based on the above-mentioned observation using glass coating, the scale morphologies after the hot rolling are classified into three categories as follows,

(a) *Ductile*. Without any cracks or fractures. Scale deforms uniformly with matrix steel. In other words, scale shows sufficient plasticity and ductility. Both outermost surface and scale/steel interface are smooth.
(b) *Mixed*. With cracks running in the thickness direction (ND). Cracks are formed near the outermost surface, however, not run throughout the scale thickness.
(c) *Brittle*. Fragmented into small pieces. In other words, the scale is very brittle. The fragmented scale is indented to the steel so that the scale/steel interface is rough.

The scale morphology changes to (a), (b) and (c) in order with decreasing rolling temperature and with increasing scale thickness. The above three categories will be used for qualitative description of scale morphologies below.

3. Prediction of scale deformation during hot rolling

3.1. Steady-state analysis of temperature distribution

It is known that the ductility of Wustite (FeO) strongly depends on the deformation temperature [7]. The above-mentioned complicated behaviors may be explained if the real temperature of the scale during hot rolling is known. The strong dependence on thickness may also be explained by the temperature. So a thermal

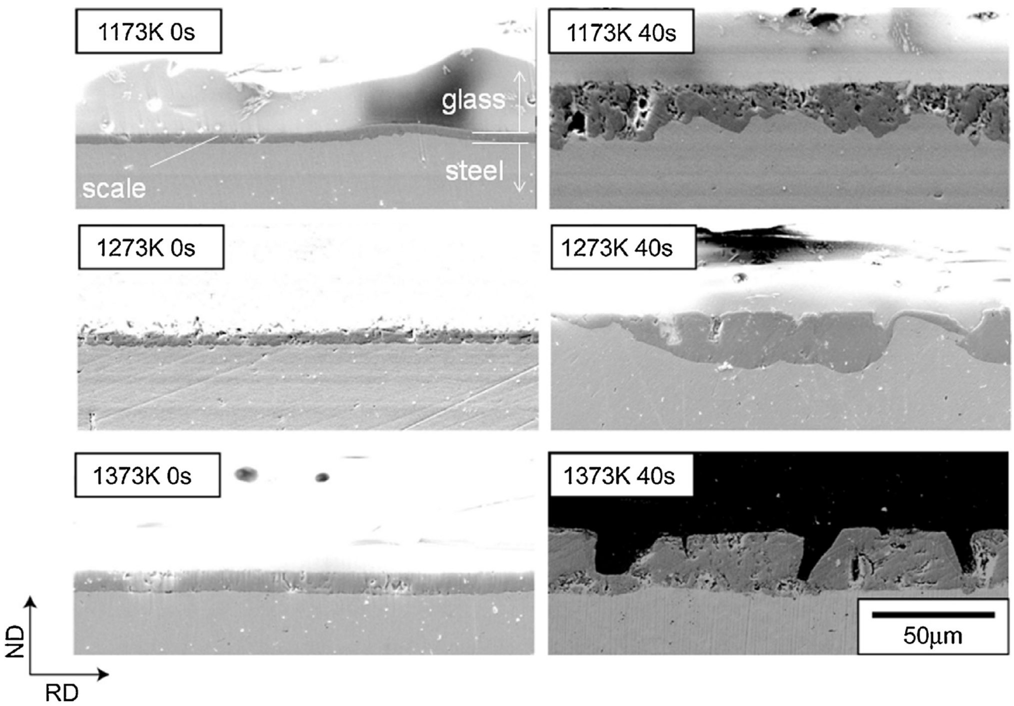

Fig. 2. SEM micrographs of oxide scale on 30% hot-rolled sheets as a function of rolling temperature T and oxidation duration before rolling t.