

# Evaluation model of susceptibility to Cu hot shortness of Cu-containing LC steel

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**Abstract.** It is well known that copper causes the hot shortness problem when in the scrap based steelmaking process. Hot shortness occurs because of selective oxidation of the iron whereby the more noble copper is enriched at the steel-oxide interface and embrittlement take places during hot working. In this paper, in order to control the Cu hot shortness, the evaluation model of susceptibility to Cu hot shortness was investigated. We found that Cu hot shortness susceptibility is related to the oxidation rate, the copper equivalence and the scale-steel interface length ratio. Also, it is founded to exist a fairly nice correlation between the oxidation rate and other factors such as chemistry elements, oxidation conditions, especially the Ni content.

## 1. Introduction

Recycling of scraps in the EAF (Electric Arc Furnace) steelmaking process has become very important from the viewpoint of economic and environmental aspect [1]. Recycling of steel scrap accumulates undesirable impurity elements such as copper, nickel and tin which are difficult to remove in steel-making process. Copper is nobler than iron and it is enriched at the steel-oxide interface when iron is oxidized at high temperature. The copper-rich liquid penetrates with time into the steel along the austenite grain boundaries, weakens the bonds and induces the surface cracking during hot working. This cracking phenomenon is known as hot shortness [2]. The other impurity elements Sn and Ni affect the evolution of copper-rich liquid phase. Tin can increase the hot shortness by decreasing the solubility of copper in austenite. On the contrary, addition of Ni can reduce hot shortness. The beneficial effect of nickel is related to an increase in the solubility of copper in austenite and occlusion in the scales [3-5]. The effect of these elements on the solubility of copper in austenite can be expressed by means of Cueq parameter ( $\text{Cueq} = \text{Cu} + 8\text{Sn} - \text{Ni}$ ) [6]. Another beneficial effect of Ni is occlusion phenomenon. This process reduces the Cu hot shortness by involving metal enriched in copper and nickel to become entrapped in the iron oxide layer. A nickel content of  $>0.02\text{wt}$  has been found to promote occlusion. The occlusion of copper-rich material into the oxide layer has a requirement: the development of a rough oxide/metal interface [7]. In addition to the impurity elements, the hot shortness also depends on the oxidation condition such as oxidation pressure, temperature, time. In general, the Cu hot shortness is most severe at temperature around  $1100^\circ\text{C}$  since the melting temperature of Cu is around  $1089^\circ\text{C}$ , resulting in the liquid Cu penetration into austenite grain boundaries [8].



In order to control and minimize the Cu hot shortness, it is necessary to understand the Cu hot shortness behavior during high temperature oxidation and establish a reliable evaluation method for Cu hot shortness quantitatively. The present work is undertaken to examine the effect of the important factors such as impurity elements and oxidation conditions on hot shortness quantitatively. Accordingly, on the basis of some theory reports and the experimental results, the evaluation model of susceptibility to Cu hot shortness is suggested.

## 2. Experimental Procedure

The chemical composition of the steels used in this study is listed in Table 1. They were melted in a vacuum furnace and the 30mm thickness ingots were hot forged. Specimens for oxidation experiment were cut to rectangular shapes of 20mm\*15mm\*3mm. Rectangular specimens were polished with #600 grit emery paper for the oxidation experiments. A steel specimen was first heated to 1010°C and held at this temperature for ten minutes in flowing high purity Ar. Then, the inert gas was replaced by the selected oxidizing gas mixture (3%O<sub>2</sub>-9%CO<sub>2</sub>-17%H<sub>2</sub>O-N<sub>2</sub>). The specimens were isothermally oxidized for 4, 9 and 30minutes after heating to 1100°C~1200°C. Also, specimens for hot compression test with 10mm in diameter and 15mm in length were machined from the ingots. The specimen were then heated in the Gleeble at 1150°C, held for 9min to stabilize, and deformed at the highest axial speed resulting in a circumferential strain rate of 30mm/sec. The microstructures at the scale/steel interface after oxidation were closely observed by using scanning electron microscopy and energy dispersive X-ray spectroscopy in order to clarify the evolution of the Cu-rich phase. All images were taken in backscattered electron (BSE) mode. The Image J program was used to measure the scale-steel interface length, crack width and crack depth. The Crack index was given by the expression (1).

$$\text{crack index} = \text{crack width} \times \text{crack depth} \times \text{the number of crack} \quad (1)$$

**Table 1.** Chemical composition of steels. (wt. %)

Steel	C	Si	Mn	P	S	Cu	Sn	Ni	Cr	Al	N	Cueq
1	0.035	0.031	0.277	0.010	0.015	0.13	0.01	0.05	0.06	0.04	0.006	0.16
2	0.035	0.031	0.277	0.010	0.015	0.22	0.02	0.08	0.11	0.04	0.006	0.30
3	0.035	0.031	0.277	0.010	0.015	0.38	0.04	0.13	0.19	0.04	0.006	0.57

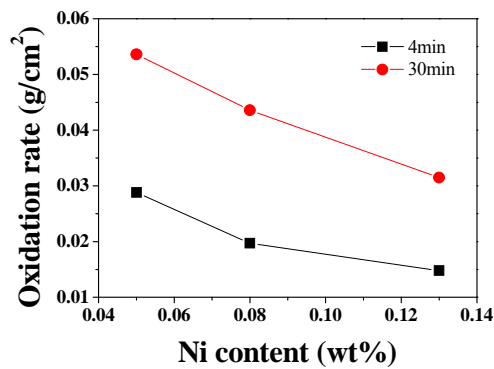
## 3. Results and Discussion

### 3.1. The effect of Ni content on the steel oxidation behaviour

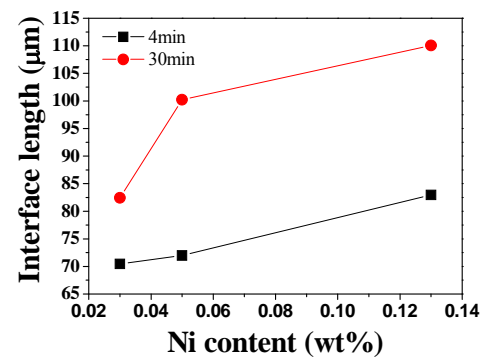
As mentioned above, the Cu-liquid phase occurs during high temperature oxidation and is closely related to the chemistry parameters and oxidation conditions. The fairly nice correlation is founded that the oxidation rate and effective factors such as temperature [T], time [t], pressure [P] and Ni content influence each other and play a significant role in the oxidation behavior of steel surface. In order to investigate the relationship between oxidation rate and other factors in detail, a careful statistical analysis has been performed. Analysis result is expressed by using the following equation (2).

$$\Delta W/A = -0.184 + 0.000175 [T] + 0.0006 [t] + 0.00193 [P] - 0.167 [Ni] \quad (2)$$

From the expression, it is seen that the Ni content has a crucial influence on the oxidation rate. The relationship between Ni content and the oxidation rate is shown in Figure 1. In Figure 1 the oxidation rate reduces with increasing the Ni content. It has been reported that addition Ni make the scale-steel interface uneven and the uneven scale-steel interface provides a channel for the occlusion and further alleviate the Cu hot shortness. Figure 2 shows the relationship between Ni content and the scale-steel interface length, showing that the scale-steel interface length increase with an increase in Ni content.



**Figure 1.** Effect of Ni content on the oxidation rate at 1150°C.



**Figure 2.** Effect of Ni content on the scale/steel interface length at 1150°C.

### 3.2. Model Development

On basis of given mechanism such as selective oxidation behavior, solubility and occlusion, the evaluation model of susceptibility to Cu hot shortness was investigated. Generally speaking, the presence of Cu-rich phase at the scale-steel interface was accompanied by surface cracking. Here, we try to evaluate the Cu hot shortness (surface cracking) by the degree of Cu enrichment at scale-steel interface, since the total enriched Cu amounts due to the oxidation should be the main origin of Cu penetration into grain boundaries. In order to measure the degree of Cu enrichment at scale-steel interface, the following operation is carried out. Firstly, the analysis describes the method that determines the maximum copper-rich amount on basis of oxidation behavior. There is the assumption that all copper is rejected from the scale and incorporated into the copper-rich layer, no diffusion of copper within the steel. The amount of copper accumulated within the copper-rich layer equals the amount of copper rejected due to scale formation during oxidation process with reference to Figure 3. The maximum amount of copper-rich can be expressed using equation (3):

$$W_{\text{Cu-rich}}^{\text{max}} = L \times C_0^{\text{Cu}} \quad (3)$$

Where  $L$  and  $C_0^{\text{Cu}}$  are the thickness of metal consumed and the initial concentration of copper, respectively. Secondly, with reference to [8], the scale thickness and the thickness of metal consumed can be calculated by equation (4) and (5), respectively.

$$X = \frac{\Delta W}{A} \times \frac{1}{K} \quad (4)$$

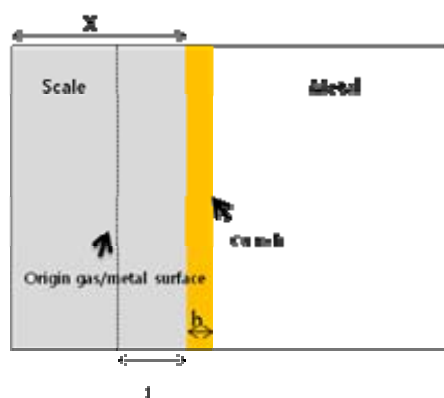
$$X = 1.84 \times L \quad (5)$$

Where  $X$  and  $\Delta W/A$  are the scale thickness and oxidation rate, respectively.  $K$  is conversion factor ( $=1.279\text{g/mm}^3$ ). Then, according to the effect of the impurity elements on the solubility of copper, taking  $C_{\text{Cu}} = C_{\text{Cu}}^{\text{eq}} = C_{\text{Cu}} + 8\text{Sn} - \text{Ni}$  was calculated as the amount of copper-rich. Lastly, incorporating the

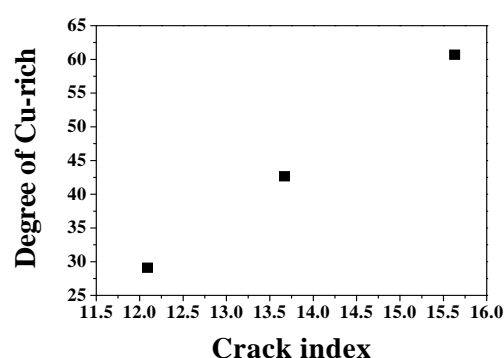
effect of the uneven interface which is a channel for occlusion on Cu enrichment into the model, the equation (3) can be modified:

$$W_{\text{Cu-rich}} = \frac{\Delta W}{A} \times \frac{\text{Cu}_{\text{eq}}}{2.35} \times \frac{H_0}{H} \quad (6)$$

Where  $H_0$ ,  $H$  and  $H_0/H$  are the initial scale-steel interface length ( $t=0$ ) and the last scale-steel interface length ( $t=t$ ) and interface length ratio respectively. Here, we use  $W_{\text{Cu-rich}}$  to judge the degree of Cu enrichment at scale-steel interface.



**Figure 3.** Schematic of arrangement of phases.



**Figure 4.** Effect of the degree of copper-rich ( $w_{\text{Cu-rich}}$ ) on the crack index.

### 3.3. The effect of the degree of copper-rich on the crack index

In order to verify the model formula (6), some data input into the model formula to obtain the enriched amount of Cu. The calculation value matched with the crack index obtained from the experimental results. Figure 4 shows the relationship between the degree of Cu-rich and the crack index. With an increase in the degree of Cu-rich phase, the cracking index becomes large. This can be explained that the more Cu-rich phase enriches at the scale-steel interface, the more opportunities occur, allowing the liquid Cu penetration into grain boundaries.

## 4. Conclusion

The simple model for evaluating the susceptibility to Cu hot shortness of Cu-containing LC steel was investigated. Addition Ni results in a decrease in oxidation rate and an increase in the scale-steel interface length. The both effect are beneficial for reducing the Cu hot shortness. The oxidation rate is expressed by formula (2) by the mean of statistical analysis. There are the fairly nice correlations between the oxidation rate and important parameters such as Ni content and time etc. The evaluation model of susceptibility to Cu hot shortness is expressed in terms of Cu enrichment characteristics such as the oxidation rate, Cu equivalence, the scale-steel interface length ratio. From this model, the degree of Cu enrichment at scale-steel interface that can predict the degree of surface cracking has been successfully calculated.

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