Note

Effects of Cu Content on the Ageing Kinetics of Cu-added Interstitial-free Steels

Jing LIU,^{1,2)} Daruo XIE,¹⁾ Dahai WANG,¹⁾
Lamei GAO,¹⁾ Mubing WEN,²⁾ Shinian LUO,²⁾
Pinghe LI,²⁾ Jianian GUI¹⁾ and Renhui WANG¹⁾

1) Department of physics, Wuhan University, Wuhan 430072 China. E-mail: rhwang@whu.edu.cn

2) Technical Center, Wuhan Iron & Steel Corporation, Wuhan 430080 China. E-mail: liyawei@usa.net

(Received on February 1, 1999; accepted in final form on March 4, 1999)

1. Introduction

The automobile industry needs to develop new materials with high strength and high drawability. As a new type of high formable high strength steel, Ti-bearing interstitial free (IF) steel strengthened by precipitation of Cu has been introduced by Kishida and Akisue.¹⁾ In order to find out optimum steel making and processing conditions for producing steel sheets of deep drawability and high strength, it is necessary to understand the ageing kinetics of Cu-containing IF steels. Although Osamura *et al.*,²⁾ Kimura and Takaki³⁾ and Morita *et al.*⁴⁾ provided some useful information about Cu-precipitation, systematic investigation about the effect of Cu content on the ageing kinetics of Cu-containing IF steels is not sufficient.

In this study, the effects of Cu content on the ageing kinetics of Cu-added interstitial-free steels have been investigated by isothermal ageing, hardness measurement and transmission electron microscopic (TEM) observation.

2. Experimental Procedures

Cu-added IF steels used in the present study were melted by a 50 kg vacuum induction furnace from conventional Ti-containing IF steel in which 0.25, 0.5, 1.0, 1.4 and 1.7 wt% Cu were added respectively. In order to avoid possible network cracking, Ni element of a half amount of Cu content was added. Steel ingots were hot-forged into slabs of thickness of 32 mm, soaked at 1150°C for 90 min, hot-rolled into 4.0 mm in thickness with a finishing temperature of 900°C, rapidly cooled to 400°C, and then cooled slowly to mimic the coiling process. The hot-rolled bands were cleaned in acid and then cold-rolled into 1.0 mm in thickness by 10 times reductions.

Cold-rolled steel sheets were treated for solution of Cu at 850°C for 30 min followed by either water-quenching or air-cooling which are referred to as W and A respectively. After solution treatment, samples with

different Cu contents were aged in a salt-bath furnace at 500°C, 550°C and 600°C respectively for different lengths of time followed by water-quenching.

Each value of Rockwell B hardness (HRB) was obtained by averaging five measurements. For TEM observation specimens were ground to the thickness of about 30 μm , punched into discs of 3 mm diameter, and electrolytically polished by the twin jet method. TEM observation was carried out by using a JEM-2000FX microscope operated at 200 kV.

3. Results

3.1. Isothermal Ageing Experiments

HRB values against the ageing time τ in second for each Cu content of the IF steels are shown in **Figs. 1(a), 1(b), 1(c) and 1(d)** for the ageing temperatures of 500°C, 550°C, 600°C and 550°C respectively. Before ageing these samples had been solution-treated at 850°C for 30 min and subsequently water quenched [Figs. 1(a), 1(b) and 1(c)] or air-cooled [Fig. 1(d)]. In these figures, W and A indicate water-quenched and air-cooled specimens after solution treatment respectively, and $\tau=0$ corresponds to as soluted states. Figure 1 reveals that:

(1) Hardness increases with increasing Cu content for all the studied states, including solution-treated and subsequently water-quenched or air-cooled states, and the aged ones. The hardening effect of Cu is more significant in the IF steels with Cu contents equal to or larger than 1.0 wt% compared with the IF steels with Cu contents equal to or less than 0.5 wt%.

(2) For the IF steels containing 1.4 or 1.7 wt% Cu, the hardness becomes higher at the early stage of ageing, and after arriving at the maximum hardness, it decreases because of overageing. With decrease of Cu content, the hardness value decreases and the time required for peak hardness increases, and in the case of the IF steel containing 1.0 wt% Cu the peak of hardness was not observed.

(3) Decreasing the ageing temperature increases the time required for getting peak hardness and the peak hardness value.

(4) In solution-treated state, hardness values of water-quenched samples are higher than those of air-cooled ones for the IF steels with Cu content of 0.25, 0.5 and 1.0 wt%, and are lower for the steels with Cu content of 1.4 and 1.7 wt%. However, there is no significant difference in the ageing kinetics between water-quenched and air-cooled samples.

3.2. TEM Observations

Precipitates and microstructures of some representative samples were observed by TEM. In the IF steel with Cu content of 1.7 wt% which was overaged at 600°C for 3600 s, about two third of the observed grains contain plate-like structures where no Cu precipitates are discernible. In one third of grains, dispersed fine Cu precipitates with diameters of 4 to 15 nm were observed as shown in **Fig. 2(a)**. No Cu precipitates were observed in the specimens with 0.25 wt% Cu aged at 600°C for 3600 s (**Fig. 2(b)**) and aged at 500°C for 8 hr. In the

Fig. 1. HRB values against the ageing time τ for different Cu contents and different ageing temperatures T .
(a) $T=500^{\circ}\text{C}$ W, (b) $T=550^{\circ}\text{C}$ W, (c) $T=600^{\circ}\text{C}$ W, (d) $T=550^{\circ}\text{C}$ A

Fig. 2. Transmission electron micrographs of specimens aged at 600°C for 3600 s.
(a) 1.7 wt% Cu, (b) 0.25 wt% Cu

solution-treated specimens with 0.25, 1.0 and 1.7 wt% Cu, no Cu precipitates were observed as well.

4. Discussions

Conventional TEM study in the present work revealed that Cu-rich precipitates of size of 4 to 15 nm were observed in the overaged IF-steel containing 1.7 wt% Cu while no discernible precipitates were found in the deficiently aged IF steels and in the IF ones at the peak hardness. This fact is considered that the ageing hardening shown in Fig. 1 is caused by Cu precipitation. As indicated by Osamura *et al.*,²⁾ at the early stage of ageing, body-centred cubic (bcc) Cu clusters nucleate and keep coherency with the bcc supersaturated Fe-Cu matrix. The coherency strain causes hardening and such an effect increases with the growth in size of the clusters. Then these bcc clusters transform to face-centred cubic (fcc) ϵ -Cu precipitates and lose their coherency with the bcc matrix, when they exceed a critical radius which is around 1.6 nm. Further growth of the ϵ -Cu precipitates leads to the density decrease of precipitates and hence the hardening effects are decreased. Thus our TEM observation results are in reasonably good agreement with those reported by Osamura *et al.*²⁾

The present study reveals that the ageing kinetics is strongly dependent on the ageing temperature and the Cu content of IF steel. The observed fact that increasing the ageing temperature accelerates the ageing kinetics and decreases the maximum hardness may be interpreted by accelerated diffusion and a smaller quantity of Cu which can precipitate because of smaller degree of supersaturation at higher temperature. When the ageing temperature is too high and the degree of the supersaturation becomes too small, the free energy decrease resulting from precipitation is too small and hence nucleation of Cu clusters would become very slow. And the another observed fact that the hardening effect

is increased and accelerated by the increase of Cu content may be interpreted by large difference in the free energy between the supersaturated and equilibrium states which leads to large nucleation rates, and by a large amount of Cu available for the formation of precipitates which leads to large growth rates and maximum hardness.

REFERENCES

- 1) K. Kishida and O. Akisue: *Tetsu-to-Hagané*, **76** (1990), 759.
- 2) K. Osamura and H. Okuda: *ISIJ Int.*, **34** (1994), 359.
- 3) Y. Kimura and S. Takaki: *ISIJ Int.*, **37** (1997), 290.
- 4) M. Morita, K. Sato and Y. Hosoya: *ISIJ Int.*, **34** (1994), 92.