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# Physical Simulation and Experimental Examination of ε-Cu Particles Dissolution Evolution During Welding of Copper Precipitation Strengthening Steel

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**Abstract**: The kinetics of ε-Cu particles dissolution in the matrix during welding of a copper-precipitation strengthening steel was determined by a combination of Gleeble™ physical simulation, TEM examination and hardness measurement. The ε-Cu particles underwent a coarsening and part dissolution and then complete dissolution reaction as the peak temperature increased from 750 to 1 000 ℃, which resulted in the decrease in the number density of ε-Cu particles and hardness in the heat-affected zone (HAZ). The results can be used to understand the evolution of this transformation and a softening behavior of the HAZ during welding of this type of steel.

**Key words**: ε-Cu particle dissolution; hardness; kinetics; steel; welding; physical simulation

The precipitation of copper-rich particles, depending on alloy composition, can play a significant role in material hardening of an as-aged structure[1-3]. Copper precipitation strengthened steels with a combination of high weldability, corrosion resistance and excellent mechanical properties have been developed for naval and cryogenic applications[4-5]. When the steel is subjected to welding, however, two competitive processes, as particle coarsening reaction and particle dissolution, may result in a variation in the volume fraction and size distribution of the precipitates in the heat-affected zone. Actually, the copper precipitates, depending on the peak temperature of welding thermal cycle, can partly or completely dissolve into the matrix of the heat-affected zone, which was observed in the HAZ of as-welded HSLA100 steel by J Y Yoo[6] and HSLA80 steel by D Dunce[7], and was believed to be one of the main causes of a softened zone contained in their welds. However, this transformation evolution dependence on the peak temperature of welding thermal cycle, which can be conveniently examined by physical simulation of the specified HAZs performed in a Gleeble™ dynamic simulator[8], has not been thoroughly dealt with previously.

In this study, using a combination of Gleeble physical simulation, TEM observation and Vickers' hardness measurement, the copper precipitate dissolution evolution during welding of a copper-containing steel and the effect of this transformation on the hardness of the HAZ were investigated.

## 1 Experimental Procedures

The cylindric specimens of $\phi 6$ mm×80 mm for HAZ simulations were made from a commercial steel plate (C 0.044, Si 0.520, Mn 1.070, P 0.016, S 0.005, Cu 0.740, Cr 0.540, Ni 0.720, Mo 0.240, Nb 0.045, Ti 0.020, B 0.001, N 0.002 9, and balance of Fe by mass percent). The welding thermal cycles were calculated from the combination of a linear tempera-

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ture-time program in heating stage and Christensen's equation[9] in cooling stage:

$$T=T_o+vt \tag{1}$$

$$T=T_o+(T_p-T_o)\exp\left[-\frac{T_p-T_o}{t_{8/5}}\cdot\left(\frac{1}{773-T_o}-\frac{1}{1\,073-T_o}\right)t\right] \tag{2}$$

where $T_o$ is the preheat temperature; $T_p$ is the peak temperature of thermal cycle; $v$ is the heating rate; and $t_{8/5}$ is the time in which the HAZ is cooled from 800 to 500 ℃. Fig. 1 shows the calculated welding thermal profiles for the HAZ simulation of manual arc welding.

The specimens were cut crosswise along the thermal couple joint for examination after the simulations. Vickers' hardness was measured using an HD9-45 sclerometer, and the particle morphology and chemical microanalysis were examined in a JEOX FX-2000 transmission electron microscope (TEM) equipped with an energy dispersive spectrometer (EDS). The slices for TEM observation were ground into 80 m and electropolished in a Fischione twin-jet unit using a solution of 10% perchloric acid in glacial acetic acid. A Leco 2001 image analyzer was used to statistically characterize the particles photographed by TEM. For each simulated HAZ, a total of 10 fields were examined at a magnification of 10×. The particle average diameter $\phi_{av}$ and the areal density $N_a$ were obtained directly from the particle analysis. The number density $N_v$ and volume fraction of particles $f$ were calculated from the following stereometric relationships:

$$N_v=\frac{N_a}{\phi_{av}} \tag{3}$$

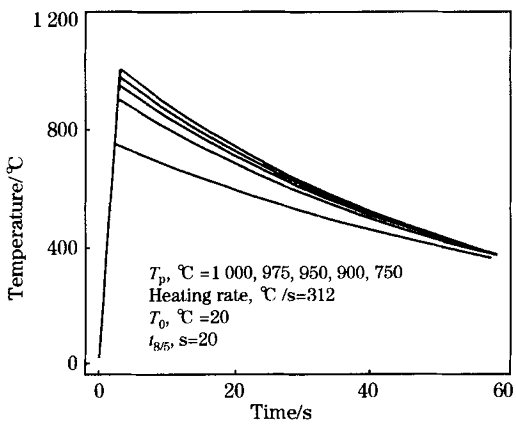


**Fig. 1 Calculated welding thermal cycles at different peak temperature for HAZ simulations**

and

$$f=\frac{\pi}{6}N_v\phi_{av}^3 \tag{4}$$

## 2 Results and Discussion

### 2.1 TEM observations

Fig. 2 (a) shows precipitates that distributed randomly in the as-tempered base metal. The particles were in spherical shape and with an average diameter of 10 nm. The EDS microanalysis indicated that the precipitates were Cu-rich particles. The selected area diffraction (SAD) pattern confirmed Kurdjumor-Sachs orientation relationship between the Cu-rich particles and the α-Fe phase. Based on Othen's observations[3], these precipitates were ε-Cu particles with FCC structure.

Fig. 3 shows a series of micrographs revealing the ε-Cu particles dissolution evolution dependence at the peak temperature for various thermal cycles. When the steel was heated to 750 ℃ during welding, the ε-Cu particles appeared to be present in a larger size and a slightly less number density in the HAZ than that of particles contained in the base metal. It was suggested that the ε-Cu particles undergo a coarsening reaction under this thermal cycle. In a simulated HAZ with the peak temperature of 950 ℃, the ε-Cu particles suffered from a decrease in both the number density and the average diameter in comparison to that distributed in the formerly simulated HAZ, which inferred that a part dissolution of ε-Cu particles had occurred. The number density of Cu-rich precipitates further decreased as the peak temperature continuously increased to 975 ℃.

While the peak temperature increased to 1 000 ℃, as shown in Fig. 4, the number density of Cu-rich precipitates dramatically decreased. Attempts using EDS microanalysis and SAD to locate possible existence of Cu-rich particles revealed that most of them were (Nb, Ti) (C, N) precipitates with the diffraction pattern for the [$\bar{1}$12] axis zone of FCC structure, which inferred that the ε-Cu particles had almost completely dissolved into the matrix.

As a matter of fact, particle coarsening occurs typically via Ostwald ripening at temperatures well below the equilibrium solvus of the precipitates, while particle dissolution gradually governs the transformation as the temperature increases. Nevertheless, it is believed that two processes can be separated, since the reaction kinetics is essentially different. Coarsening is driven by the surface energy alone,