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An ultrafast performance regeneration of aged stainless steel by pulsed electric current

Xuebing Liu, Xinfang Zhang *

School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, PR China

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ABSTRACT

It has been proved thermodynamically that the dissolution of the precipitates is directly related to the temperature, that is, if the critical temperature cannot be reached, the precipitates can only grow and the precipitation process continues. Therefore, the reverse thermodynamic dissolution behavior of the precipitates under certain conditions will become very significant. Here we provide a new pathway to investigate the dissolution behavior of highly thermally stable precipitates under electropulsing. Our findings show that the change of free energy caused by the difference in electrical conductivities between the precipitates and matrix leads to the inverse thermodynamic precipitates' dissolution.

Austenitic stainless steels are widely used as structural materials in nuclear power main pipeline due to their excellent high temperature strength and corrosion resistance [1–3]. Long-term high temperature service of nuclear power devices resulted in a dramatically degradation of mechanical properties due to the thermodynamic growth of the dispersion-strengthened precipitates [2–6]. The disaster of nuclear leakage caused by steel performance degradation is devastating, thus the demand for rapid regeneration of performance-degraded stainless steel is extremely robust. Heat treatment is definitely the most general method to dissolve the precipitates [7–10], but this kind of ex-situ processing method has limitations for on-site service pipelines. Although numerous investigations had been published with respect to precipitation temperature, location, morphologies, precipitation kinetics as well as precipitate stability [3,6,8,11], the inverse thermodynamic precipitates' dissolution behavior that can be used in situ under certain conditions is rarely reported. Pulsed electric current, as an instantaneous high energy input method with high efficiency and low energy consumption, had been applied to the metallic materials to modify the microstructure and properties in a short time. The precipitates in Al alloys, Mg alloys and nanoscale χ phase in 316 L stainless steel can be dissolved by electropulsing [12–15]. The $M_{23}C_6$ and σ phases, as the most abundant precipitate in stainless steels, required higher temperature to be dissolved due to their excellent thermal stability. The σ phases can be removed from cast austenite stainless steels at an annealing temperature of 1050 °C [7,10], while the $M_{23}C_6$ phases began to dissolve at 850 °C [9]. Nevertheless, the dissolution of large-sized microscale precipitates below the critical temperature of heat treatment has not been reported under pulsed-based processing. The above questions will be addressed in this study.

Here, 316 N stainless steel containing 0.08C, 17.0Cr, 12.0Ni, 2.0Mo, 2.0Mn, 0.75Si and 0.16 N was used for investigation. The steels were cold-rolled from 3.0 mm to 0.5 mm with 83.3% reduction, and then were aged at 750 °C for 24 h to obtain coarse precipitates. From the SEM images of the aged samples in Fig. 1, it can be seen that the size of the bright precipitates varies from several hundred nanometers to several micron (Fig. 1a). According to statistics, the ratio of precipitates larger than 1 μm is 1/4, and the rest is less than 1 μm (Fig. 1b). The number of precipitates per unit area is approximately $3.3 \times 10^5/mm^2$. By TEM characterization (sample prepared using a double-jet electropolisher with a electrolyte consisting of a mixture of 90% ethanol and 10% perchloric acid at −25 °C), the precipitates are determined to be $M_{23}C_6$ (M = Cr) and σ phases (Fig. 1c and d). Heat treatment was further performed for the aged samples at 700 °C for 1 h, a large number of bright dispersed precipitates were observed in the matrix (Fig. 2a), and the number of precipitates per unit area is approximately $6.7 \times 10^5/mm^2$ (Fig. 2b). This shows that there is no dissolution of the precipitates at 700 °C, instead it promotes the precipitation process (e.g. number increased by 2 times).

However, when the pulsed current was applied to the aged steels, the dissolution of the precipitates has taken place. Fig. 2c shows the microstructure of the pulsed steel, and only a small amount of fine precipitates can be observed. The number of particle per unit area is $1.8 \times 10^3/mm^2$ (Fig. 2d). For this case, Joule heating induced by current provides a temperature of 700 °C. In comparison to the number density under the same temperature aging, the pulsed current greatly dissolves the precipitates (e.g. number decreased by 370 times). To clarify this type of dissolution phenomenon, TEM observations in Fig. 3 reveal the

* Corresponding author.
E-mail address: xfzhang@ustb.edu.cn (X. Zhang).

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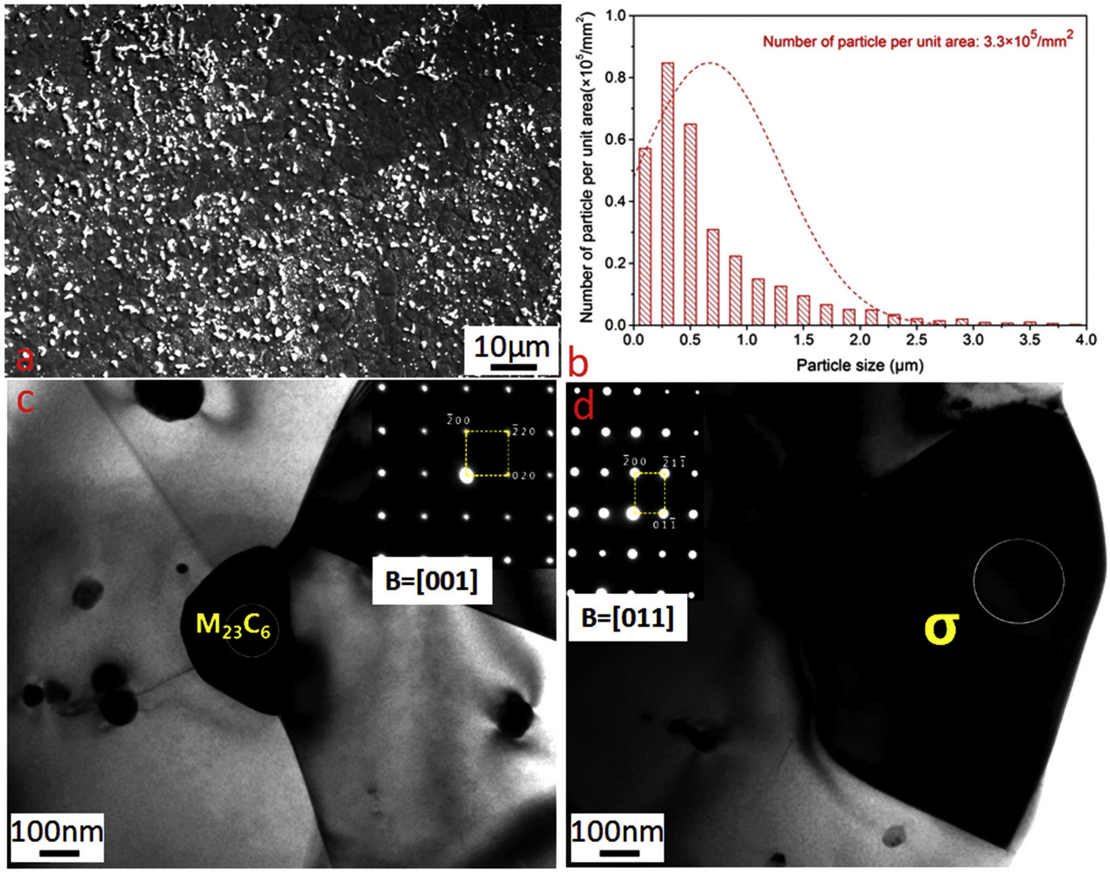

Fig. 1. (a) the distribution of bright precipitates in the aged sample at 750 °C for 24 h, (b) the number and size distributions of precipitates for the aged sample, (c) selected area diffraction pattern of $M_{23}C_6$ phase, and (d) selected area diffraction pattern of σ phase.

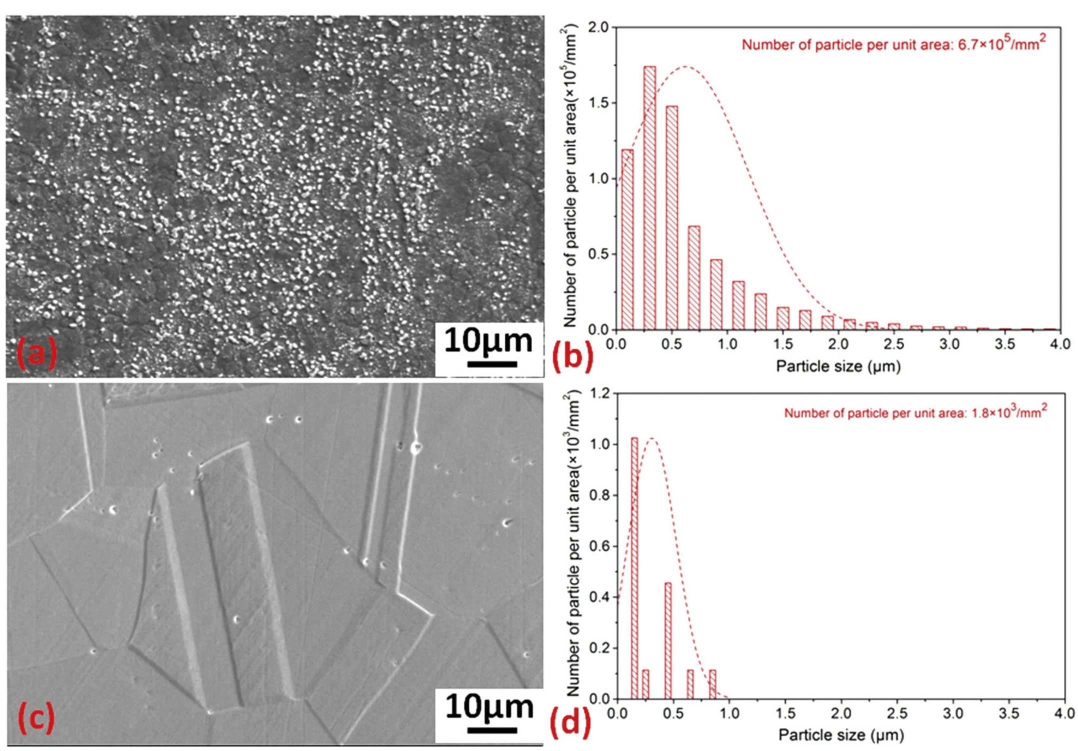

Fig. 2. (a) the distribution of bright precipitates in the aged sample followed by annealing at 700 °C for 1 h, (b) the number and size distributions of precipitates for the annealed sample, (c) the distribution of precipitates in the aged sample followed by pulsed treatment for 1 h, and (d) the number and size distributions of precipitates for the pulsed sample.