Minor Hysteresis Loop Analysis for Magnetic Granular Systems with Local Distribution

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***Abstract*—Minor hysteresis loop measurements were performed for sensitized Alloy 600 with magnetic granular system around the grain boundary. The experimental results showed the difference depending on the distribution of Cr depletion and were analyzed by Monte Carlo simulation. Calculation results tell the possibility of coexistence of domain wall displacement and super paramagnetism.**

***Index Terms*—magnetic hysteresis, Monte Carlo method, magnetic analysis, Nickel alloys**

I. Introduction

The Nickel-base super alloy Alloy600 (Inconel) has slight magnetism on grain boundaries under sensitization due to degradation by thermal heat treatment, although it has non-magnetism originally. The magnetic behavior depends on the degree of sensitization. Therefore recently relationship between magnetic properties and sensitization is focused with expectation for potentiality of nondestructive evaluation (NDE) [1]-[3]. Several experimental reports show the magnetism around grain boundary is caused by Cr depletion under sensitization. We have investigated the change of the magnetic properties such as magnetic hysteresis (B-H) curves depending on Cr depletion distribution using Monte Carlo (MC) simulation [4]. Then full B-H curves with saturation magnetization region were explained well by each Cr depletion distributions like the total amount and the density of the depletion. The relationship between full B-H curves and Cr depletion distribution due to the degree of sensitization would be very useful to check the degradation level especially for initial steps without any cracks which cannot be detected by supersonic testing method.

On the other hand, the magnetism on grain boundaries in Alloy 600 is of particular interest as a unique magnetic granular system with local distributions, although usual magnetic granular systems have averagely homogeneous density of magnetic sites. There is a possibility that the magnetization process does not follow one due to the domain wall (DW) displacement for bulk materials. Then we tried to measure and simulate minor hysteresis loops for sensitized Alloy 600 with different thermal heating duration time (T_D) which controls the degree of sensitization. Minor hysteresis loops are B-H curves under applied magnetic field less than saturated magnetization field and they are expected to reveal magnetic dynamic process. Actually, for bulk samples of ferromagnets, minor loop is used for the estimation of magnetic quality [5].

In this paper, experimental results of minor hysteresis loop for sensitized Alloy 600 are analyzed by MC simulation.

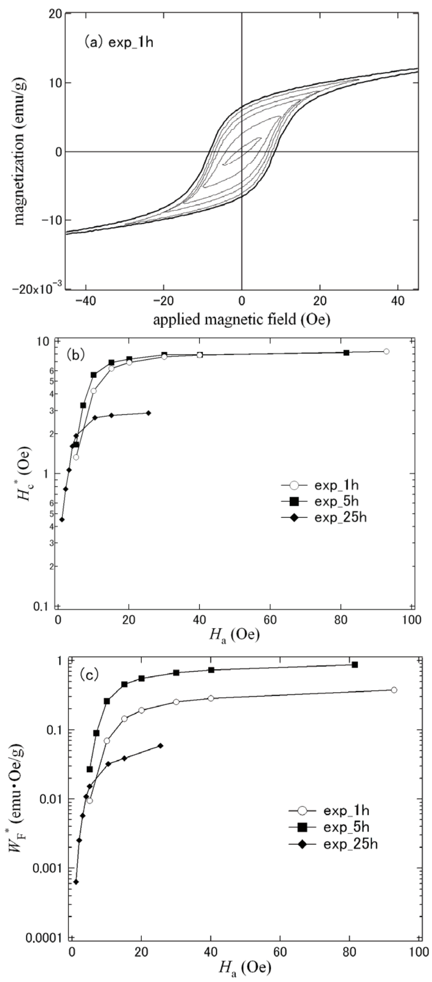

Fig. 1. Experimental results of minor hysteresis loops for sensitized Alloy 600 at room temperature. (a) Minor hysteresis loop for Alloy 600 with T_D= 1 h. (b) Max applied magnetic field H_a dependence of coercivity H_c^* for Alloy 600 with T_D= 1h, 5h and 25h. (c) H_a dependence of hysteresis loss W_F^* for each minor loops.

II. Experement of Minor Hysteresis Loop

Sensitized Alloy 600 with thermal heating duration time of 1 hour (1h), 5 hours (5h) and 25 hours (25h) were prepared as minor hysteresis loop measurement samples. The measurement of minor loops was performed at room temperature using vibration sample magnetometer (VSM). Figure 1(a) shows minor loops for the 1hour sample and it is clearly seen that loops shrink depending on the decrease of max value of applied magnetic field (H_a) of each minor loop, although the magnetic field ranges are small comparing with usual minor loops for bulk samples. Figure 1(b) and 1(c) show H_a dependence of coercivity H_c^* and hysteresis loss W_F^* for minor loops. For the sample with T_D=25h, H_c^* is saturated at weaker field than 1h and 5h samples. The result concerns with the distribution of magnetic sites around grain boundaries as shown the next section.

III. Calculation of Minor Hysteresis Loop

Average distribution of Cr depletion around grain boundary for sensitized Alloy 600 can be observed by Energy Dispersive X-ray spectrometry (EDX). The distributions of magnetic sites along x-axis of the cubic system composed of 31^3 cells ($0 \le x \le 30$, $0 \le y \le 30$, $0 \le z \le 30$) corresponding to the distribution of Cr depletion are shown in Fig.2.

A following Hamiltonian was used for the MC simulation:

$$H = H_J + H_D + H_B$$
$$= -\sum_{near} J_{ij} \boldsymbol{S}_i \boldsymbol{S}_j + D \sum_{all} \left(\frac{\boldsymbol{S}_i \cdot \boldsymbol{S}_j}{|\boldsymbol{r}_{ij}|^3} - \frac{3}{|\boldsymbol{r}_{ij}|^5} (\boldsymbol{S}_i \cdot \boldsymbol{r}_{ij})(\boldsymbol{S}_j \cdot \boldsymbol{r}_{ij}) \right) + B \sum_i \boldsymbol{S}_i . \quad (1)$$

H_J term, H_D term and H_B term represent exchange interaction energy, magnetic dipole interaction energy and applied magnetic field energy, respectively. In this simulation, the parameters were set as J_{ij} =1.0, D=0.02. The value of $\boldsymbol{S}_i$, which denotes the magnetic moment of the site of i-th, was fixed as $|\boldsymbol{S}_i|$=1.

Figure 3(a) shows the calculation result of minor loops for the cluster with T_D=1h. It is clearly seen that the model follows well to the experimental result in Fig.1(a). The H_a dependences of H_c^* and W_F^* have also good correspondence with experimental ones as shown in Fig. 3(b) and 3(c). The H_a dependence of H_c^* for the cluster with T_D=25h shows quick saturation as same as experimental one. Spin snap shots on magnetization process for the cluster tell the behavior of spins shows multiple place reversal magnetization like super-paramagnetism, although DW displacements are observed for the clusters with T_D=1h and 5h. This analysis might suggest a possibility of coexistence of DW and super-paramagnetism around grain boundaries of Alloy 600.

IV. Conclusion

Minor loop simulation using MC method for Alloy 600 with local magnetic distribution followed well to the experimental result. The simulation could tell also the complex coexistence of DW and super-paramagnetism.

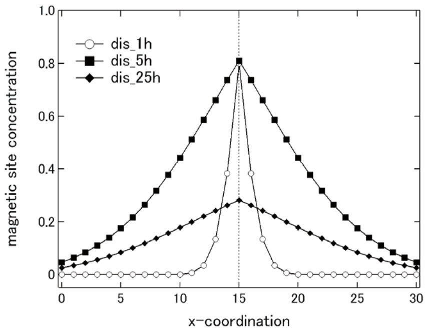

Fig. 2. Distributions of magnetic sites along x-axis for model magnetic cluster of T_D= 1h, 5h and 25h by estimation from EDX results.

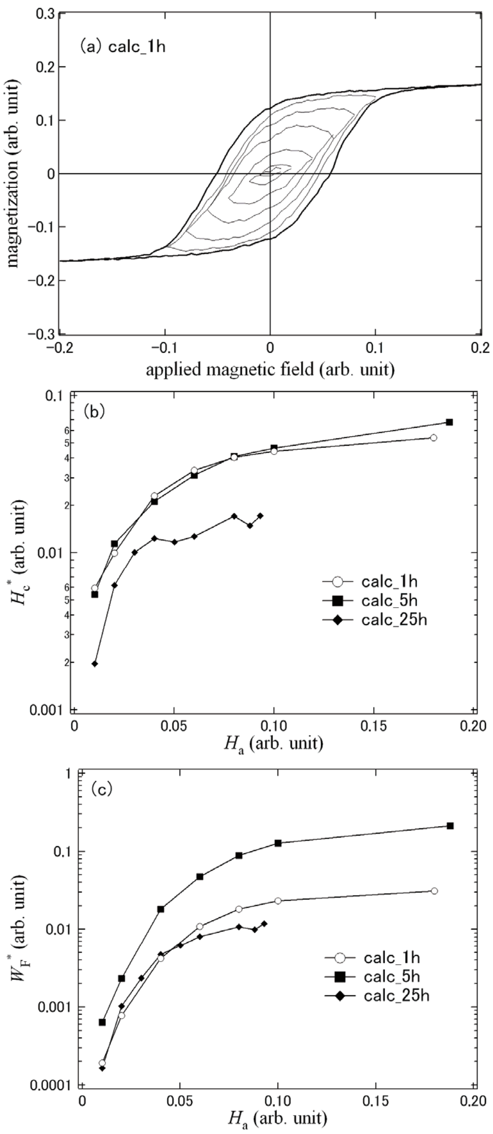

Fig. 3. Calculation results of minor hysteresis loops for clusters with different T_D. (a) Calculated minor hysteresis loop for the cluster with T_D= 1 h. (b) Calculated H_a dependence of H_c^* for the clusters with T_D= 1h, 5h and 25h. (c) H_a dependence of W_F^* for each calculated minor loop.

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