Temperature dependence of magnetic properties for sensitized Alloy 600

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Abstract — Alloy 600 (Inconel 600) is one of austenitic Ni-Cr-based superalloys, and it's important that the sensitization for Alloy 600 is detected earlier to examine degradation degree. We focused on discrete distribution of Cr depletion and simulated magnetization process using Monte Carlo method. For the simulation, we built the sensitized clusters with different annealing duration time, which were considered the magnetism of both grain and grain boundary region. The simulation contains temperature dependence of magnetization and magnetic hysteresis curves and they were compared with experimental ones, especially on coercivity and Curie temperature.

I. INTRODUCTION

Alloy 600 (Inconel 600) is one of austenitic Ni-Cr-based superalloys. This alloy is used well as structure materials in such as nuclear power plants because of its high mechanical strength and corrosion resistant. For this alloy, it is known that sensitization, which is one of material degradation phenomenon, is caused by inappropriate heat history and sensitization could cause intergranular stress corrosion cracking (IGSCC) [1]-[3]. The progress of sensitization also causes change of magnetic properties due to Cr depletion around grain boundary. Therefore, the relation between the progress of sensitization and the change of magnetic properties has been investigated quantitatively associating with nondestructive evaluation (NDE) [4].

Annealing Alloy 600 under the constant temperature can have different sensitization degree depending on thermal heating duration time. In our previous study, we obtained the results that the discrete distribution degree of Cr depletion contributes to the magnetic properties of Alloy 600 such as coercivity or remanence comparing the results between experiment and simulation [5]. Furthermore, the simulation results suggested that the Curie temperature of Alloy 600 depends on the sensitization degree.

Figure 1 shows experimental results of temperature dependence of magnetization for Alloy 600 which was annealed for each duration time under 650ºC. It was measured by superconducting quantum interference device (SQUID) magnetometer and the applied magnetic field was 100 Oe. The results show lager magnetization under 100K. It's seems to be come from the properties of grain region, that is, paramagnetic region changes to ferromagnetic under 100K. The magnetic property of this matter was also reported by Takahashi [6]. For this reason, we need to consider the magnetic property including grain region.

In this paper, simulation was performed considering the magnetism of grain and grain boundary region and compared with experimental results on temperature dependence of coercivity and annealing duration time dependence of Curie temperature.

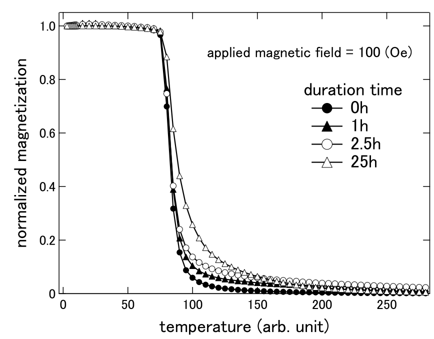

Fig. 1. Temperature dependence of magnetization was measured by SQUID magnetometer with different annealing duration time at 650ºC. Applied magnetic field was 100 Oe. The magnetization was normalized by the magnetization of the lowest temperature.

II. NUMERICAL METHODS

To simulate magnetization process of sensitized Alloy 600, modeled clusters around grain boundary were built based on discrete distribution of Cr depletion. The Cr depletion can be obtained from Cr concentration, which is calculated using thermal equilibrium and one-dimensional diffusion equation [4]. Figure 2 shows sensitized clusters, which has 31^3 sites ($0 \le x \le 30$, $0 \le y \le 30$, $0 \le z \le 30$). The grain boundary was set to x=15 and annealing duration time was 0h, 1h, 2.5h or 25h.

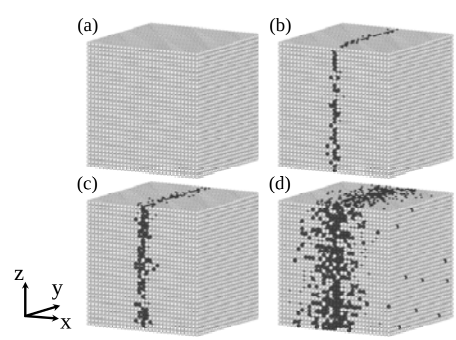

Fig. 2. Sensitized clusters with each duration time: (a) 0h, (b) 1h, (c) 2.5h and (d) 25h. The black points represent ferromagnetic sites at room temperature due to Cr depletion and white ones are paramagnetic sites.

The simulation was performed using Monte Carlo method which is based on Metropolis sampling. Here, Hamiltonian includes terms of exchange interaction H_J and external magnetic field H_B:

$$H = H_J + H_B = -\sum_{near} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \sum_{i} \boldsymbol{B} \cdot \boldsymbol{S}_i . \qquad (1)$$

The site of cluster has two different value of spin because the area of grain region is much lager than that of grain boundary, that is, $|\boldsymbol{S}|=1$ in grain boundary region, $|\boldsymbol{S}|=50$ in grain region, respectively. The exchange interaction constant J has three variations in the strength thus: $J_1=5000$, $J_2=1$, $J_3=0.02$, these are in case of interaction between ferro- ferro, ferro-para, para-para magnetic sites, respectively. Here, we regard that ferromagnetic sites are black points and paramagnetic sites are white points in Fig. 2.

For more details about the simulation method, refer to previous works [7]-[9].

III. RESULTS AND DISCUSSION

Figure 3 shows simulation results of temperature dependence of magnetization. The magnetization was normalized to 50, which ratio are (grain) : (grain boundary) = 49 : 1. As increasing of annealing duration time, clusters tend to magnetize earlier and the tendency coincides with experimental one as shown in Fig. 1.

Figure 4 shows simulation results of magnetic hysteresis curves of each temperature with the cluster which annealing duration time is 2.5h. The temperature dependence of coercivity is shown in Fig. 5. The coercivity increases as increasing of temperature in both case of simulation and experiment.

Furthermore, we analyzed Curie temperature in grain boundary region as shown in Fig. 6. The results are good coincidence on temperature dependence of Curie temperature between simulation and experiment.

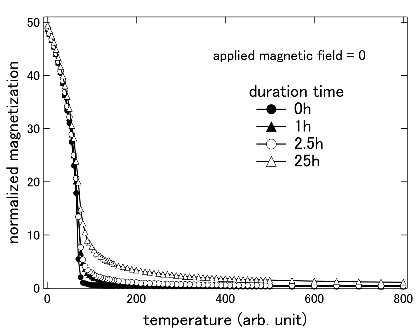

Fig. 3. Simulation results of temperature dependence of magnetization curves each duration time. Applied magnetic field was set to 0.

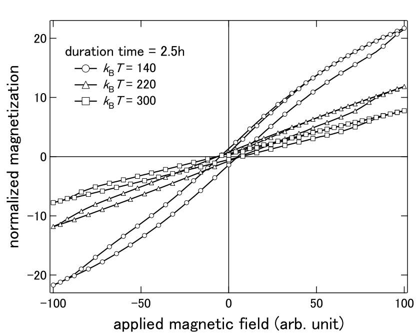

Fig. 4. Simulation results of magnetization curves under different temperature with the cluster which annealing duration time is 2.5h.

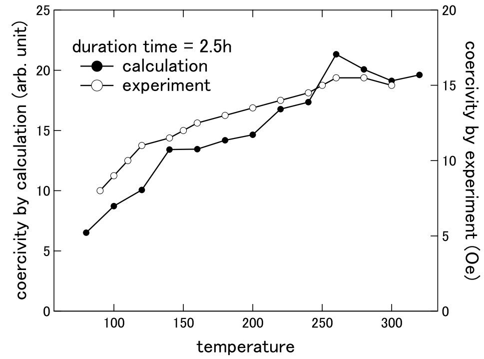

Fig. 5. Temperature dependence of coercivity of experiment and calculation with duration time of 2.5h. The unit of temperature is Kelvin (K) in experiment and arbitrary unit (a.u.) in calculation.

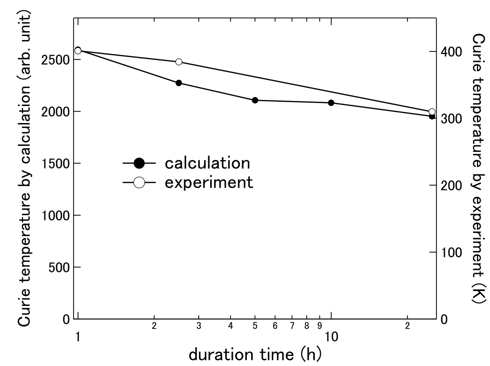

Fig. 6. Curie temperature dependence of annealing duration time in grain boundary region by experiment and calculation.

IV. REFERENCES

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