Correlation between Grain Boundary Segregation of Alloying Elements and Grain Refinement Strengthening in Ferritic Steels

周, 裕雄

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氏　　名　：周　裕雄

論 文 名　：Correlation between Grain Boundary Segregation of Alloying Elements and Grain Refinement Strengthening in Ferritic Steels
（フェライト鋼の結晶粒微細化強化と合金元素の粒界偏析の関係）

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Thesis Summary

This study investigated the relationship between the Hall-Petch coefficient (k_y) and the concentration of grain boundary (GB) segregation in Fe-C binary and Fe-C-(Mn/Si) ternary alloys. The Hillert-Ohtani (HO) model's GB segregation evaluation method was verified experimentally compared with the traditional McLean model. The influence of annealing temperature and interaction between interstitial element: C with substitutional elements: Mn and Si on the k_y was discussed. The conclusions are summarized as follows:

Chapter 1 introduced the background and research objectives of this study.

In Chapter 2, it was purposed to find an accurate method to calculate the concentration of GB segregation and figure out the exact relationship between the k_y and segregated C/N concnentration at the GB. The concentrations of C and N segregated at the GB in Fe-(C/N) binary alloys were estimated using the McLean and the HO models. The comparison between the two models' calculated results and experimental values obtained by the three-dimensional atom probe tomography (3DAP) revealed that the HO model could gain more precise results than the McLean model. In addition, C exhibited a stronger tendency of GB segregation than N, which will decrease the N concentration at GB when co-added. In this Chapter, it was indicated that the k_y was linearly related to the calculated concentrations of segregated C at GB, the k_y can be predicted from the chemical composition and heat treatment temperature via thermodynamic calculations.

In Chapter 3, it was proposed that the k_y can be correlated with the solubility of C in Fe-C alloys by extending the study of the predicting formula obtained in Chapter 2. Based on the calculated results of the

HO model, the reduction of annealing temperature will improve the GB segregation level. The k_y of Fe-50C ferrite steels was studied by annealing treatment under different temperatures to verify this. The results of experimental k_y were almost coordinated with the predicted values by the HO model, which makes the quantitative description reasonable for various C content and annealing temperature in Fe-C alloys. At the end of Chapter 3, a three-dimensional diagram was drawn to summarize the relationship among the C content, the solution temperature, and the k_y in Fe-C alloys. With the help of this diagram, the k_y can be predicted and controlled in further studies.

In Chapter 4, the procedure was to confirm the influence on the k_y by co-addition of interstitial and substitutional elements and gain high k_y alloys. Based on Chapters 2 and 3, C has a strong tendency to segregate at the GB, significantly affecting the k_y. In addition, previous studies also indicated the apparent enlargement of the k_y by Mn and Si addition in Fe-Mn/Si binary alloys. To find out whether the co-addition of C with Mn or Si can gain higher k_y or not, Fe-Mn-C and Fe-Si-C ternary alloys were investigated. Both ternary alloys exhibited larger k_y than Fe-C binary alloys. In these two multi-systems, the equilibrium and para-equilibrium situations were considered to estimate the concentration of GB segregation. Due to the different diffusion rates of C and Mn/Si, the para-equilibrium was considered more reasonable. With this equilibrium theory, the k_y of Fe-Mn-C alloys can be predicted by the additional effects of segregated C and Mn. On the contrary, the k_y of Fe-Si-C was much greater than the predicted ones. This effect might come from the interaction between Si and C at the GB.

Chapter 5 finally summarized the results of Chapters 2, 3, and 4.