Diffusion of Chromium in α -Iron

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Tracer diffusion coefficient of ^{51}Cr in α -iron has been determined by a serial radio-frequency sputter-microsectioning method in the temperature range 885 to 1174 K. In α -iron of the paramagnetic state from the Curie temperature to the α - γ transformation temperature the diffusion coefficient of chromium shows a linear Arrhenius relationship with negligible influence of the short range magnetic spin ordering. Below the Curie temperature, temperature dependence of the diffusion coefficient deviates from the linear Arrhenius relationship owing to the magnetic spin ordering. Taking into account the influence of the magnetic transformation, the temperature dependence of the diffusion coefficient, D , in the whole temperature range of α -iron across the Curie temperature can be expressed by

$$D = (3.73_{-1.40}^{+2.24}) \times 10^{-3} \exp \left[-\frac{(267.4 \pm 4.4 \text{ kJ} \cdot \text{mol}^{-1})[1 + (0.133 \pm 0.005)s^2]}{RT} \right]$$

$\text{m}^2 \text{s}^{-1}$, where s is the ratio of the spontaneous magnetization at T K to that at 0 K. The factor (0.133) in the above equation is smaller than 0.156 in the case of the self-diffusion in α -iron, indicating that the influence of the magnetic transformation on the diffusion of chromium in α -iron is smaller than that on the self-diffusion, as expected from the negative magnetic moment of chromium atom in the lattice of ferromagnetic iron.

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I. Introduction

Measurement of sub-micron diffusion profiles of radioactive tracers in solids by the sputter-microsectioning method⁽¹⁾⁽²⁾ enables us to determine diffusion coefficients as small as $10^{-23} \text{ m}^2 \text{s}^{-1}$. Recent great progress in solving various problems of diffusion behavior in solids has been made mainly by using this technique⁽³⁾. One of the problems to be solved has been the influence of the magnetic transformation on diffusion, which was found first in self-diffusion in α -iron at the beginning of 1960's⁽⁴⁾⁽⁵⁾ and subsequently in diffusion of various elements in α -iron⁽⁶⁾. In those experiments, the traditional mechanical sectioning techniques were mainly used which limited the measurable diffusion coefficient to larger than $10^{-16} \text{ m}^2 \text{s}^{-1}$ ⁽⁷⁾. This is nearly equal to the self-diffusion coefficient of iron at the Curie temperature ($T_c = 1043 \text{ K}$)⁽⁸⁾. Therefore, the self-diffusion coefficient of iron in the ferromagnetic state could be determined down to only 70 K below the Curie temperature, T_c ⁽⁵⁾, and temperature dependence of it could not be revealed in detail. However, in 1977 Hettich *et al.*⁽⁹⁾ succeeded in lowering the limit of the diffusion temperature to 259 K below T_c of iron by a new technique, the ion-beam sputter-microsectioning. Their work stimulated many investigators to study on this topic, that is, the influence of

the magnetic transformation on diffusion⁽¹⁰⁾. In succession to the study on self-diffusion in α -iron⁽⁹⁾, Mehrer and his co-workers have investigated self-diffusion in cobalt⁽¹¹⁾ and diffusion of cobalt⁽¹²⁾⁽¹³⁾ and nickel⁽¹⁴⁾ in α -iron. The present authors have used a serial radio-frequency sputter-microsectioning method with radioactive tracers to study self-diffusion in α -iron⁽¹⁵⁾ and cobalt⁽¹⁶⁾ and diffusion of cobalt in α -iron⁽¹⁷⁾ and iron-12 at% cobalt alloy⁽¹⁸⁾.

In all the cases of experimental results mentioned above, the Arrhenius plot of diffusion coefficients in the ferromagnetic state deviates downwards from the Arrhenius relationship extrapolated from the paramagnetic state. The equations describing such temperature dependence of the diffusion coefficients in the whole temperature range across the Curie temperature have been proposed by several workers such as Ruch *et al.*⁽¹⁹⁾, Hettich *et al.*⁽⁹⁾, Kučera⁽²⁰⁾ and Braun and Feller-Kniepmeier⁽²¹⁾. Ruch *et al.*⁽¹⁹⁾ have proposed an equation:

$$D = D_0^p \exp \left[-Q^p(1 + \alpha s^2)/RT \right]. \quad (1)$$

D_0^p and Q^p are the frequency factor and the activation energy for the self-diffusion, respectively, in the paramagnetic state. The value of s , the ratio of the spontaneous magnetization at T K to that at 0 K, has been experimentally determined by Potter⁽²²⁾ and Crangle and Goodman⁽²³⁾. The constant α expresses the extent of the influence of the magnetic transformation on diffusion, and given by

$$\alpha = \frac{\alpha_f + \alpha_m}{Q^p}, \quad (2)$$

where α_f and α_m are the increments of formation energy

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and migration energy, respectively, of a vacancy by the magnetic transformation. α_f is related to the exchange integral J between a jumping atom and a nearest neighbor atom in the equilibrium position and the coordination number z by $\alpha_f = zJ/2$, and estimated to be $4.3 \text{ kJ} \cdot \text{mol}^{-1}$ for iron by Ruch *et al.*⁽¹⁹⁾ α_m is related to the exchange integral J^* between a jumping atom in the saddle point and a nearest neighbor atom by $\alpha_m = cJ^*$ where c is a constant. Unfortunately, theoretical calculation of α_m is impossible at present because of the great difficulty in calculating J^* . Using literature data on s , Hettich *et al.*⁽⁹⁾ as well as Ruch *et al.*⁽¹⁹⁾ have fitted their experimental data to eq. (1) and estimated the values of D_0^p and Q^p and the constant α . Furthermore, Hettich *et al.*⁽⁹⁾ have substituted the term $\alpha_m s^2$ by the elastic constant and fitted their experimental data on the self-diffusion in α -iron to eq. (1) better than that by Ruch *et al.*⁽¹⁹⁾

On the other hand, taking into account the influence of the short range magnetic spin ordering on diffusion above the Curie temperature, Kučera⁽²⁰⁾ has expressed the temperature dependence of the diffusion coefficient in iron by a more complicated equation than eq. (1). Referring the experimental data by Hettich *et al.*⁽⁹⁾ on α -iron and by Lai and Borg⁽²⁴⁾ on Fe-1.8 at%V alloy in the temperature range 973 to 1773 K, Kučera has emphasized the significant influence of the short range magnetic spin ordering above the Curie temperature. Braun and Feller-Kniepmeier⁽²¹⁾ have simplified Kučera's theoretical treatment by using the experimental data on the magnetic excess enthalpy, and they have analyzed the experimental data on self-diffusion in α -iron⁽⁹⁾ and diffusion of cobalt⁽¹²⁾⁽²⁵⁾, chromium⁽²⁶⁾⁽²⁷⁾, copper⁽²⁸⁾, zinc⁽²⁹⁾ and antimony⁽³⁰⁾ and also suggested a large influence of the short range magnetic spin ordering on the diffusion of those elements in α -iron above its Curie temperature. However, the self-diffusion coefficient in α -iron obtained by the present authors⁽¹⁵⁾ has shown a linear Arrhenius relationship from the Curie temperature to the α - γ transformation temperature (1184 K) without any influence of the short range magnetic spin ordering in contrast to the analyses by Kučera⁽²⁰⁾ and by Braun and Feller-Kniepmeier⁽²¹⁾, although the diffusion coefficient of cobalt in α -iron obtained by the present authors⁽¹⁷⁾ has shown a non-linear Arrhenius relationship above the Curie temperature in agreement with the experimental data obtained by Mehrer and his co-workers⁽¹²⁾⁽¹³⁾.

All the impurity diffusion coefficients of chromium⁽²⁶⁾⁽²⁷⁾, copper⁽²⁸⁾, zinc⁽²⁹⁾ and antimony⁽³⁰⁾ in α -iron used in the analyses by Feller-Kniepmeier and her co-workers have been obtained not by the impurity diffusion experiment but by the interdiffusion experiment where the impurity diffusion coefficients have been estimated by extrapolating the interdiffusion coefficient in alloys to infinite dilution of the solute in the alloys. Thus, their experimental data must be examined from the following view points. As well known, the concentration-dependent interdiffusion coefficient can be calculated from a concentration(C)-distance(X) curve by Matano's method⁽³¹⁾, provided that the $C-\lambda$ ($\lambda = \sqrt{X/t}$) curve is

independent of diffusion time (t). If the diffusion time is short, the diffusion zone has steep concentration gradients and local strains which produce progressive recrystallization and other nonsteady structural effects. Such conditions probably lead to the generation of excess vacancies or short circuiting paths, which lead to apparent increase of interdiffusion coefficient⁽³²⁾. According to Borovskiy *et al.*⁽³³⁾, the reliable interdiffusion coefficient in binary alloys of the complete solid solutions can be obtained using pure metals couples, if the diffusion time is long enough to produce the diffusion zone thicker than $130 \mu\text{m}$. Usually, as in the case of the interdiffusion experiments by Feller-Kniepmeier and her coworkers, the concentration-distance curve is measured by the electron probe microanalyzer (EPMA). The diameter of the electron beam of EPMA is about $1 \mu\text{m}$ under the best conditions with which the secondary X-rays of the elements to be analyzed in the specimen are emitted from the area, centered at the electron beam spot, about $10 \mu\text{m}$ in diameter. Thus, in the light of the EPMA technique, a long penetration distance more than $100 \mu\text{m}$ is also required to obtain a reliable concentration-distance curve. However, at lower temperatures where the influence of the short circuiting diffusion via dislocations on the penetration profile is unavoidable even in a well-annealed specimen, the diffusion coefficient should be determined from a very short penetration profile in the order of the mean distance between dislocations. Such a diffusion measurement cannot be carried out by the EMPA technique. Therefore, determination of the impurity diffusion coefficient at lower temperatures based on the interdiffusion experiments by the EPMA technique is not suitable. Thus, re-examination of impurity diffusion in α -iron by the sub-micron techniques with radioactive tracers must be most appropriate to elucidate the influence of the magnetic transformation on impurity diffusion in α -iron.

In contrast to cobalt atom which has a large positive magnetic moment ($2.1\mu_B$) as a solute in iron⁽³⁴⁾, chromium atom has the largest negative magnetic moment ($-3.4\mu_B$) among the 3d transition elements dissolved in iron⁽³⁵⁾. Thus, diffusion behavior of chromium in α -iron above and below the Curie temperature is interesting in comparison with that of cobalt. So far, tracer diffusion of ^{51}Cr in α -iron has been studied by Bowen and Leak⁽³⁶⁾ and Huntz, Aucouturier and Lacombe⁽³⁷⁾. However, these studies have been concentrated only above the Curie temperature. The present work has been carried out to examine in detail the diffusion coefficient of chromium in α -iron across the Curie temperature. For the diffusion of the radioactive tracer ^{51}Cr , a serial radio-frequency sputter-microsectioning method, the same as in our work on self-diffusion in α -iron⁽¹⁵⁾, has been used.

II. Experimental Procedure

High purity electrolytic iron, "Atomiron XL" supplied by Showa Denko Co., was vacuum-melted in an alumina crucible and refined in a hydrogen gas at-

mosphere of 101 kPa for 900 s and cast into a steel mold 25 mm in diameter after substitution of hydrogen by argon. The ingot was hot-forged and machined to 12 mm in diameter. To cause grain growth and reduce the contents of carbon, nitrogen and oxygen, the rod was annealed at 1753 K in the δ -iron phase region for 86.5 ks in a stream of hydrogen gas purified by permeation through a palladium tube at 700 K and passed through a liquid nitrogen trap. The resultant grain size was about 6 mm, and the contents of carbon, nitrogen and oxygen would be less than 1 mass ppm, respectively, as suggested by Wada and Sakamoto, the developer of this method⁽³⁸⁾. The rod was cut to make the disc specimen 4 mm in thickness. The flat face of the specimen was ground on water-proof abrasive papers and polished with fine alumina paste (particle size: 0.3 or 0.06 μm). To obtain a stress-free surface, the specimen was annealed at 1073 K for 10.8 ks in a stream of purified hydrogen gas.

The radioisotope ^{51}Cr (γ -ray, 0.320 MeV; half-life, 27.7 d) was supplied in a form of CrCl_3 in 0.5 kmol m^{-3} HCl solution from ICN Biochemicals Inc., U. S. A. The radionuclidic purity of the isotope was more than 99%. The radioisotope was electroplated on the surface of the specimen from the solution. The specimen was diffused at temperatures in the range from 885 to 1174 K for 3.00 ks to 536 ks in furnaces controlled within ± 1 K in a stream of purified hydrogen gas.

The serial sputter-microsectioning method⁽³⁹⁾ was employed to measure the penetration profiles of the radioisotope into the specimen. The specimen was set on a target in the radio-frequency sputtering apparatus. By applying radio-frequency power with a peak-to-peak voltage of 1.6 kV at 13.56 MHz the specimen was sputtered in an argon glow discharge. The sputtered-off material was collected on an aluminium foil. The serial sectioning of the whole profile was achieved by moving the collector foil step by step like a roll film in a camera without interrupting the radio-frequency supply. For each specimen 15–30 successive sections were sputtered. The section thicknesses were determined from the sputtering rate and the individual sputtering time. In each run, the sputtering rate was determined from the total sputtering time and total reduced thickness which was determined by analyzing the interference step between the protected and sputtered parts of the surface measured by an interferometric microscope. The total reduced thickness was also estimated by the total weight loss. A constant fraction more than 60% of the sputtered-off material could be collected on the aluminium foil. The intensity of γ -ray from each section was measured by a well-type Tl-activated NaI scintillation detector in conjunction with a 1024 channels pulse height analyzer.

III. Results

For one-dimensional volume diffusion of a tracer from an infinitesimally thin surface layer into a sufficiently long rod, the solution of Fick's second law is given by

$$I(X, t) \propto C(X, t) = \frac{M}{\sqrt{\pi Dt}} \exp\left(-\frac{X^2}{4Dt}\right), \quad (3)$$

where $I(X, t)$ and $C(X, t)$ are the intensity of the radioactivity and the concentration, respectively, of the tracer at a distance X from the original surface after diffusion time t . D is the volume diffusion coefficient of the tracer and M is the total amount of tracer deposited on the surface before the diffusion.

Figures 1, 2 and 3 show the plots of $\ln I(X, t)$ vs X^2 for the diffusion of ^{51}Cr in α -iron at higher, middle and lower temperatures, respectively. In proof of eq. (3), all the plots in Figs. 1, 2 and 3 show linearity, and thus it can be said that the volume diffusion has been concerned. The diffusion coefficients calculated from the slope of the plot are listed in Table 1, and the Arrhenius plot of them is shown in Fig. 4 in comparison with those by Bowen and Leak⁽³⁶⁾ and Braun and Feller-Kniepmeier⁽²⁶⁾. The diffusion coefficients of chromium in α -iron of the paramagnetic state determined by the present work are lower than those by the other authors, but show a linear Arrhenius relationship between the Curie temperature

Fig. 1 Examples of penetration profiles for diffusion of ^{51}Cr in α -iron at temperatures higher than 1107 K.

[†] Twenty-four substitutional impurities have been analyzed. Their total concentration is less than 54 ppm. Interstitial impurities are C:34, N:36, O:220 and H:9 ppm.

Fig. 2 Examples of penetration profiles for diffusion of ^{51}Cr in α -iron at temperatures between 1037 and 1087 K.

Fig. 3 Examples of penetration profiles for diffusion of ^{51}Cr in α -iron at temperatures lower than 928 K.

and the α - γ transformation temperature with the frequency factor, D_0^p , $(3.73_{-1.40}^{+2.24}) \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and the activa-

Table 1 Diffusion coefficient of ^{51}Cr in α -iron.

Temperature (K)	Diffusion time (s)	Diffusion coefficient ($\text{m}^2 \text{ s}^{-1}$)
1174	3.00×10^3	4.67×10^{-15}
1171	3.60×10^3	4.76×10^{-15}
1155	3.00×10^3	3.31×10^{-15}
1152	3.60×10^3	2.61×10^{-15}
1149	3.60×10^3	2.35×10^{-15}
1141	3.69×10^3	2.08×10^{-15}
1125	3.60×10^3	1.39×10^{-15}
1110	3.60×10^3	1.14×10^{-15}
1107	3.60×10^3	9.20×10^{-16}
1095	3.60×10^3	6.47×10^{-16}
1087	3.60×10^3	4.17×10^{-16}
1074	3.60×10^3	3.56×10^{-16}
1062	4.20×10^3	2.93×10^{-16}
1055	3.60×10^3	2.08×10^{-16}
1049	3.60×10^3	1.90×10^{-16}
1037	7.20×10^3	8.08×10^{-17}
1034	4.20×10^3	8.62×10^{-17}
1026	7.32×10^3	5.05×10^{-17}
1021	7.26×10^3	3.53×10^{-17}
1017	4.80×10^3	2.84×10^{-17}
993	1.38×10^4	1.20×10^{-17}
974	1.80×10^4	3.35×10^{-18}
968	5.79×10^4	3.32×10^{-18}
944	1.44×10^5	1.23×10^{-18}
938	6.33×10^4	6.68×10^{-19}
928	1.41×10^5	4.32×10^{-19}
928	1.41×10^5	3.75×10^{-19}
927	1.64×10^5	3.47×10^{-19}
894	6.48×10^4	8.68×10^{-20}
885	5.36×10^5	3.72×10^{-20}

tion energy, Q^p , $(267.4 \pm 4.4) \text{ kJ} \cdot \text{mol}^{-1}$ without any influence of the short range magnetic spin ordering. Also, in the ferromagnetic state the diffusion coefficients determined by the present work are lower than those by Braun and Feller-Kniepmeier⁽²⁶⁾, and the difference between them increases with decrease of temperature.

IV. Discussion

As shown in Fig. 4, the diffusion coefficient of chromium in α -iron of the paramagnetic state determined by the present experiment is smaller than those by the other authors, Huntz *et al.*⁽³⁷⁾ have determined the diffusion coefficient of ^{51}Cr in α -iron above the Curie temperature by the residual activity method. Although their experimental data are not shown in Fig. 4 to avoid confusion, they are in agreement with the data by Bowen and Leak⁽³⁶⁾. According to the recent theoretical analysis by LeClaire and Rabinovitch⁽⁴⁰⁾, to avoid the apparent increase of volume diffusion coefficient due to diffusion via dislocations, the mean volume diffusion length, $2(Dt)^{1/2}$, should be less than $3.5 \mu\text{m}$ for well-annealed f.c.c. metals with the dislocation density 10^{10} m^{-2} . As has been discussed in our previous paper⁽¹⁵⁾, the value of $2(Dt)^{1/2}$ for α -iron should be also in the same range as that for f.c.c. metals. In the sputter-microsectioning of the present work, $2(Dt)^{1/2}$ is in the range $1.7 \sim 7.5 \mu\text{m}$ for the α -iron of the paramagnetic state. In the case of the residual ac-

Fig. 4 Arrhenius plot of diffusion coefficients of chromium in α -iron in comparison with those by other authors. Arrhenius plot of the self-diffusion coefficient in α -iron is also shown.

tivity method and the EPMA method used for diffusion of chromium in α -iron by Bowen and Leak⁽³⁶⁾ and Braun and Feller-Kniepmeier⁽²⁶⁾, respectively, $2(Dt)^{1/2}$ was obliged to be larger than in the case of the sputter-microsectioning at least by one order of magnitude. Therefore, the diffusion coefficients determined by Bowen and Leak⁽³⁶⁾ and Braun and Feller-Kniepmeier⁽²⁶⁾ must be affected by the enhancement effect due to diffusion via dislocations, which becomes more prominent with decrease of temperature, as shown in Fig. 4. According to Braun and Feller-Kniepmeier⁽²¹⁾, in the diffusion of chromium in α -iron the influence of the magnetic transformation is observed above the Curie temperature up to 1123 K. If it is true, the apparent activation energy for diffusion of chromium in α -iron of the paramagnetic state from 1123 to 1184 K (α - γ transformation temperature) should be lower than that in the temperature range from 1043 (Curie temperature) to 1123 K. However, in the present results such a tendency is never observed, and

Fig. 5 Plot of $T \ln [D(T)/D_0^p]$ vs s^2 for diffusion of chromium in α -iron of the ferromagnetic state.

a linear Arrhenius relationship is observed from the Curie temperature to the α - γ transformation temperature of pure iron. This indicates that the influence of the short range magnetic spin ordering on the diffusion of chromium in α -iron of the paramagnetic state is negligible, as in the case of self-diffusion in α -iron⁽¹⁵⁾.

Equation (1) can be rewritten as

$$\left[T \ln \frac{D(T)}{D_0^p} \right] = -\frac{Q^p}{R} - \left(\frac{\alpha Q^p}{R} \right) s^2. \quad (4)$$

Putting the values of $D(T)$ and D_0^p by the present work and the empirical value of $s(T)$ for pure iron by Potter⁽²²⁾ and Crangle and Goodman⁽²³⁾ into eq. (4), $T \ln [D(T)/D_0^p]$ was calculated as a function of s^2 , and plotted in Fig. 5. A linear relationship between $T \ln [D(T)/D_0^p]$ and s^2 is observed, indicating that in iron of the ferromagnetic state the temperature dependence of diffusion coefficient of chromium obeys eq. (1). From the slope and intercept of the straight line in Fig. 5, α and Q^p were determined and listed in Table 2 in comparison with the values for self-diffusion⁽¹⁵⁾ and diffusion of cobalt in α -iron⁽¹⁷⁾. Q^p calculated in this way is denoted by Q_{cal}^p . It is noted that the value of Q^p determined directly from the Arrhenius plot of $D(T)$ in the paramagnetic state is in good agreement with Q_{cal}^p , as shown in Table 2. Using the values of $\alpha(=0.133)$, $D_0^p(=3.73 \times 10^{-3} \text{ m}^2 \text{ s}^{-1})$ and $Q^p(=267 \text{ kJ} \cdot \text{mol}^{-1})$ obtained by the present work, $D(T)$ is

Table 2 Frequency factor, activation energy and constant α for diffusion of chromium and cobalt and self-diffusion in α -iron.

	D_0^p ($10^{-4} \text{ m}^2 \text{ s}^{-1}$)	Q^p ($\text{kJ} \cdot \text{mol}^{-1}$)	Q_{cal}^p ($\text{kJ} \cdot \text{mol}^{-1}$)	α	$Q^f = Q^p(1 + \alpha)$ ($\text{kJ} \cdot \text{mol}^{-1}$)
Self-diffusion	$2.76^{+1.42}_{-1.04}$	250.6 ± 3.8	250.5 ± 0.4	0.156 ± 0.003	289.7 ± 5.1
Diffusion of cobalt	2.76	251	—	0.23	309
Diffusion of chromium	$37.3^{+22.4}_{-14.0}$	267.4 ± 4.4	267.5 ± 0.5	0.133 ± 0.005	303.0 ± 6.3

Fig. 6 Temperature dependence of αs^2 for diffusion of chromium in α -iron in comparison with those for self-diffusion and diffusion of cobalt in α -iron.

calculated, and its Arrhenius plot is drawn as a solid line in Fig. 4. The fitting of the solid line with the experimental points of $D(T)$ is excellent. As shown in Table 2, the value of $\alpha (=0.133)$ for the diffusion of chromium in α -iron is about 15% smaller than that for the self-diffusion⁽¹⁵⁾. αQ^p , the increment of the activation energy by the magnetic transformation is $35.6 \text{ kJ} \cdot \text{mol}^{-1}$ for the diffusion of chromium, while it is $39.1 \text{ kJ} \cdot \text{mol}^{-1}$ for the self-diffusion.

The value of αs^2 can be taken as a measure to express the extent of the influence of the magnetic transformation on diffusion. Putting $D(T)$, D_0^p and Q^p into eq. (1), the values of αs^2 for self-diffusion⁽¹⁵⁾ and diffusion of cobalt⁽¹⁷⁾ and chromium in α -iron are calculated as a function of temperature and shown in Fig. 6. In the case of self-diffusion and diffusion of chromium in α -iron, αs^2 decreases gradually with increase of temperature and becomes zero at and above the Curie temperature of pure iron, although αs^2 for the diffusion of chromium is somewhat smaller than that for the self-diffusion. However, for the diffusion of cobalt in α -iron, αs^2 is larger than that for the self-diffusion in the whole temperature range and becomes zero at and above 1140 K which is 97 K higher than the Curie temperature of pure iron. This means that a local magnetic field around a solute cobalt atom is stronger than that of the iron matrix and it remains even above the Curie temperature, on the other hand, around a solute chromium atom it is slightly weaker than that of the iron matrix and becomes zero at the Curie temperature. The increased magnetic field around a diffusing cobalt atom is attributed to the positive magnetic moment of solute cobalt atom ($2.1\mu_B$ ⁽³⁴⁾) in the iron matrix. On the contrary, the decreased magnetic field around a diffusing chromium atom is attributed to the negative magnetic moment of solute chromium atom ($-3.4\mu_B$ ⁽³⁵⁾) in the iron matrix.

V. Conclusion

Applying a serial radio-frequency sputter-microsection-

ing method with radioactive tracer ^{51}Cr , the diffusion coefficient of chromium in α -iron has been determined in the temperature range 885 to 1174 K. In α -iron of the paramagnetic state from the Curie temperature to the α - γ transformation temperature, the diffusion coefficient shows a linear Arrhenius relationship without any influence of the short range magnetic spin ordering. Temperature dependence of the diffusion coefficient D in the whole temperature range of α -iron across the Curie temperature can be expressed by

$$D = (3.73_{-1.40}^{+2.24}) \times 10^{-3} \times \exp \left[-\frac{(267.4 \pm 4.4 \text{ kJ} \cdot \text{mol}^{-1})[1 + (0.133 \pm 0.005)s^2]}{RT} \right]$$

$\text{m}^2 \text{s}^{-1}$, where s is the ratio of the spontaneous magnetization at $T \text{ K}$ to that at 0 K. The factor (0.133) in the above equation is about 15% smaller than that in the similar equation obtained for the self-diffusion of α -iron, indicating that the influence of the magnetic transformation on the diffusion of chromium in α -iron is smaller than that on the self-diffusion. This is attributed to the negative magnetic moment of solute chromium atom in the iron matrix.

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