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Effect of carbon on the diffusion of copper in different carbon-steels

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Solid state diffusion is of great theoretical and practical importance. The tracer-technique can be applied to help solve many theoretical and practical problems. In this paper the thin layer method was used to study the diffusion of Cu^{64} in different carbon-steels. Experiments were performed at temperatures of 1173, 1193, 1213 and 1233 k in order to determine the diffusion coefficients of Cu^{64} in steels containing 0.2, 0.4, 0.6 and 0.8 wt% of carbon. From the results the effect of carbon content on the diffusion of Cu in steel was evaluated. Also the activation energies for the diffusion of Cu in the different specimens were calculated.

1. Introduction

The field of diffusion studies in metals and alloys is of great practical as well as theoretical importance. In recent years the study of diffusion, using small concentrations of radioactive isotopes, has resulted in the accumulation of a highly reproducible data base [1]. However, there are still some problems which remain outstanding and require further study. One of these cases is the diffusion of Cu in iron and its alloys. Linder and Karnik [2] have studied the diffusion of Cu in γ iron and have observed a large discontinuity in the diffusion coefficient of Cu in the α–γ phase. They also observed grain-boundary diffusion at low temperatures in the γ phase using a metallographic technique. They measured the chemical diffusion of Cu with a microprobe [3] and found that the activation energy for diffusion of Cu in the α phase was 249.9 kJ g atom^{-1} and in the γ phase it was 295.11 kJ g atom^{-1}. Anand and Agarwala [4], using the residual-activity technique, found that the activation energy for the diffusion of Cu in α iron in both the paramagnetic and ferromagnetic phases to be 238.6 and 246.13 kJ g atom^{-1} respectively. They also noticed a decrease in the diffusivity at the Curie point.

In a previous paper [5] the activation energies for the diffusion of Cu in the three different ranges α, $\alpha - \gamma$ and γ were found to be 196.74, 239.60 and 286.02 kJ g atom^{-1} respectively.

In this investigation the effect of carbon as the main interstitial impurity in steel on the diffusion of Cu in steel was studied using the thin layer method. [6–9].

2. Experimental procedures

The thin layer method was used to measure the diffusivity of Cu in steels having different carbon contents. The carbon was considered to be the main interstitial impurity in these steels. Thin sheets of 1020, 1040, 1060 and 1080 steels (thickness of 0.005 cm) were cut into specimens of 1×1 cm. The specimens were annealed and then polished.

The Cu^{64} was obtained by activating Cu powder of purity (99.98%) to 0.05 mCi. The γ-ray spectrum was checked and no half-life impurities were present. The activated copper was then dissolved in concentrated sulphuric acid and the solution was then diluted to ten times its volume. A filter paper moistened by the radioactive solution was used to deposit a thin film of the activated copper on one side of the specimens. The time of contact of the moistened filter paper with the surface of the specimen was 45 s in all the experiments. The samples were then washed in acetone and dried under a stream of argon. The specimens were then kept in a desiccator under vacuum. The activated copper-film thickness was about 0.02 μm.

The annealing temperatures were chosen in such a way as to permit the study of diffusion of Cu in the different steels while the iron is solely in the γ phase. The annealing temperatures were; 1173, 1193, 1213 and 1233 k for each specimen. The temperature was measured with an accuracy of $+2\,^{\circ}C$ and the annealing period was 30 min in all experiments. Fig. 1 shows a schematic diagram of the apparatus used in the annealing of the specimens.

In order to protect the specimens from oxidation during heating, the specimens were placed in a cold evacuated joint (B) and held there until the annealing tube (A) reached the required temperature, then the specimen was dropped into tube (A) by tilting the furnace assembly.

At the end of the annealing period (30 min), the specimen was transferred back into the cold joint (B) by tilting the furnace assembly in the opposite direction, and it was left there to cool under vacuum before it was transferred for the activity measurements. The number of beta particles from both sides of the thin specimen were counted using a thin anthracine crystal (thickness 3 mm with an 0.012 mm thick aluminium

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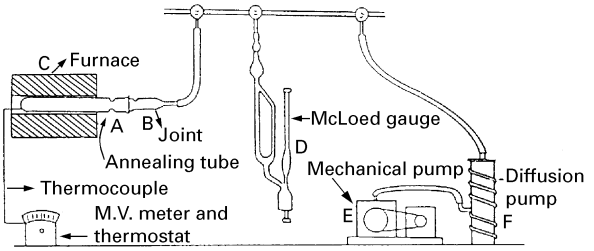

Figure 1 Schematic diagram of the experimental apparatus.

protecting cover), and the resultant count rate was determined by means of a scalar. The sample and the detector were enclosed in a lead shield. The high voltage was set to give maximum sensitivity. Both sides of the sample were counted five times for 1 min each in all experiments.

3. Results and discussion

In the thin layer method, the solution of Fick's second law $[\delta C/\delta T = -D\,(\delta^2 C/\delta X^2)]$ leads to the following kinetic equation:

$$\mathrm{Ln}(I_1 - I_2)/(I_1 + I_2) = \mathrm{Ln}\,K - (\pi^2 D/l^2)t$$

where I_1 and I_2 are the activities at time t on the coated and uncoated sides of the specimen respectively, K is a constant, independent of time and the diffusion of specimens, L is the thickness of the specimen and D is the diffusion coefficient.

In Equation 2 the relation between $[\mathrm{Ln}(I_1 - I_2/I_1 + I_2)]$ and time (t) will be a straight line. The diffusion coefficient (D) can be easily calculated from the slope of this line.

In order to study the effect of the carbon content of the steel on the diffusion rate, a series of experiments were performed at a constant temperature of 1173 k-using specimens with carbon contents of 02, 0.4, 0.6 and 0.8 wt %. The results of these experiments are shown in Fig. 2 and listed in Table I. From these results one can easily show that the diffusion coefficient of Cu in steel decreases as the carbon content in the steel increases within the range covered in this investigation.

In order to study the effect of the carbon content on the activation energies for diffusion of Cu in different carbon steels, experiments using specimens with different carbon contents at temperatures of 1173, 1193, 1213 and 1233 k were performed. The results of these experiments are shown in Figs. 3–6.

The activation energies for the diffusion were calculated from the relation between the diffusion coefficient (D) and the frequency factor (D_0) given by the Arrhenius type equation:

$$D = D_0\,\mathrm{e}^{(-Q/RT)}$$

in which D_0 is the frequency factor, Q is the activation energy for the diffusion and T is the absolute annealing temperature.

By plotting the values of (Ln D) at different temperatures against $(1/T)$ the frequency factor (D_0) and the activation energy for the diffusion (Q) can be easily calculated. Fig. 7 shows the relation between ($\log D$) and $(1/T)$ for specimens with different carbon contents. The different values of D, D_0 and Q for all the specimens as calculated from the previous figures are listed in Table II.

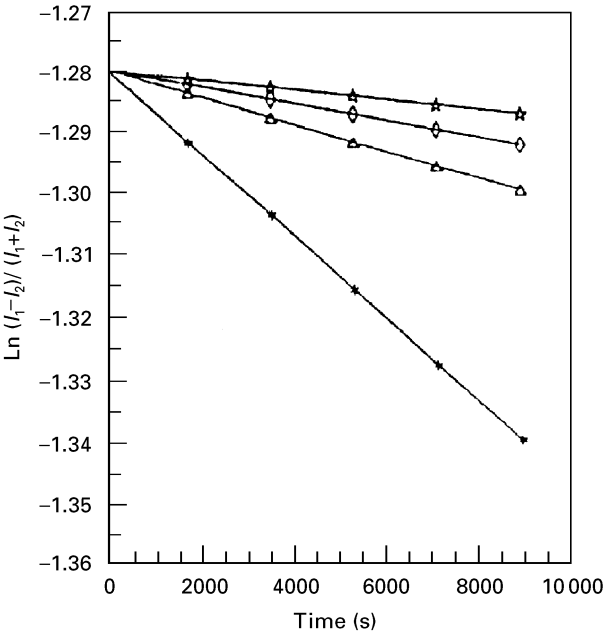

Figure 2 Kinetic curves for (★) steel 1020, (△) steel 1040, (◇) steel 1060 and (☆) steel 1080.

TABLE I Frequency factor and activation energies for different steels

Specimen	Temperature T (k)	Phase	Diffusion coefficient $\mathbf{D} \times 10^{-11}$ ($\mathrm{cm^2\,s^{-1}}$)
1	1173	γ	7.6
2	1173	γ	4.6
3	1173	γ	2.8
4	1173	γ	0.6

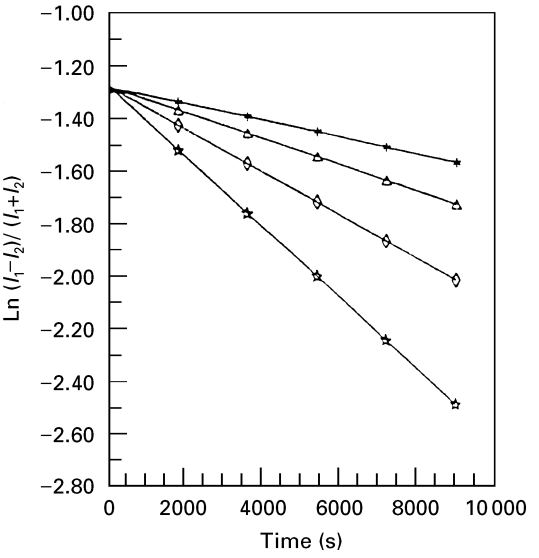

Figure 3 Kinetic curves for 0.2% C at temperatures of: (★) 1173 K, (△) 1193 K, (◇) 1213 K and (☆) 1233 K.

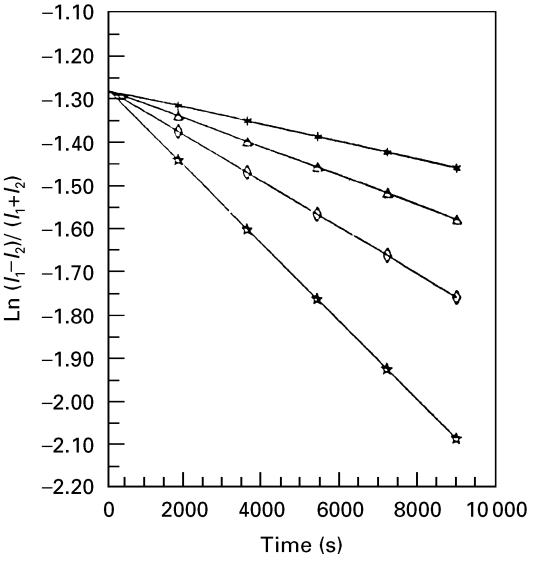

Figure 4 Kinetic curves for 0.4% C at temperatures of: (★) 1173 K, (△) 1193 K, (◇) 1213 K and (☆) 1233 K.

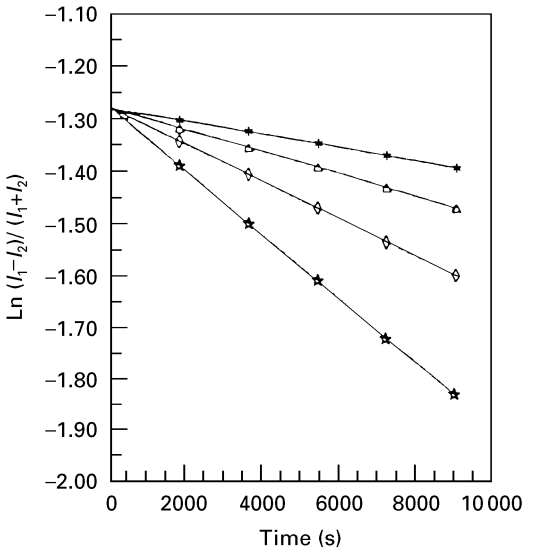

Figure 5 Kinetic curves for 0.6% C at temperatures of: (★) 1173 K, (△) 1193 K, (◇) 1213 K and (☆) 1233 K.

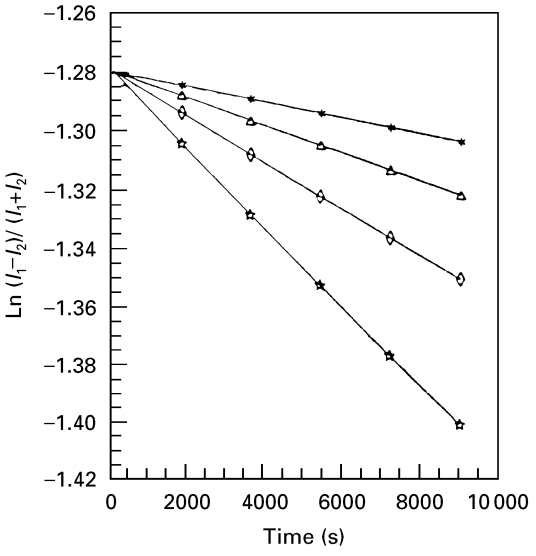

Figure 6 Kinetic curves for 0.8% C at temperatures of: (★) 1173 K, (△) 1193 K, (◇) 1213 K and (☆) 1233 K.

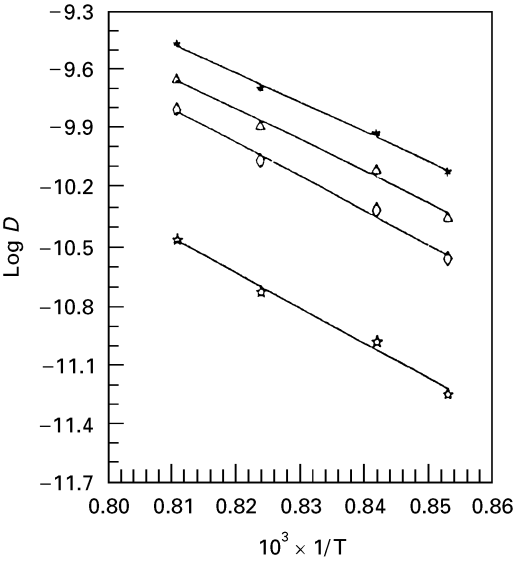

Figure 7 Arrhenius plot.

TABLE II Diffusivities, frequency factor and activation energies at different temperatures for different steels

Content (%)	T (K)	D $\times 10^{-10}$ ($cm^2 s^{-1}$)	D_0 ($cm^2 s^{-1}$)	Q ($kJ mol^{-1}$)
	1173	0.76	572	
0.2	1193	1.20	549	289.32
	1213	2.00	566	
	1233	3.30	586	
	1173	0.46	1370	
0.4	1193	0.80	1410	302.72
	1213	1.30	1390	
	1233	2.20	1440	
	1173	0.28	8800	
0.6	1193	0.50	8980	325.74
	1213	0.86	8990	
	1233	1.50	9290	
	1173	0.06	8840	
0.8	1193	0.11	9020	340.82
	1213	0.19	8850	
	1233	0.35	9420	

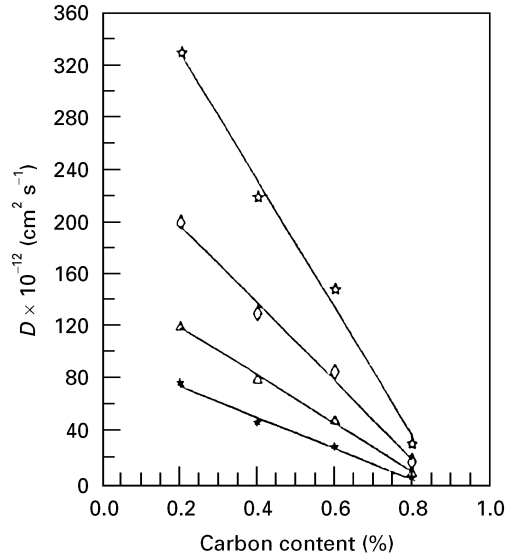

Figure 8 The effect of temperature and carbon on the diffusion rate. The temperatures investigated were: (★) 1173 K, (△) 1193 K, (◇) 1213 K and (☆)1233 K.

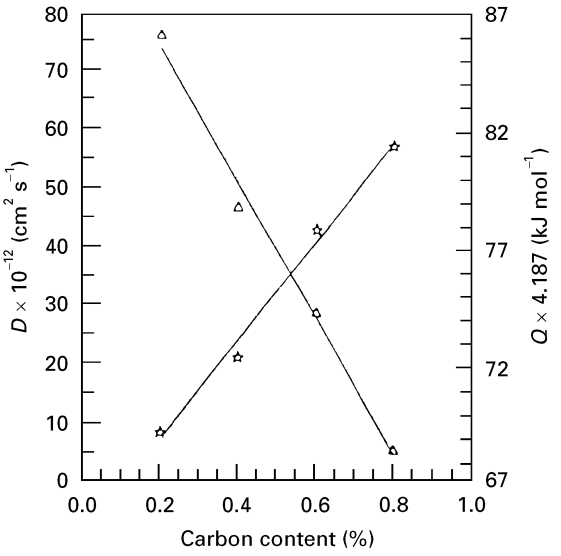

Figure 9 The effect of the carbon content of the steel on (△) the diffusion coefficient of copper and (☆) the activation energy.

Fig. 8 shows the effect of both the temperature and carbon content on the diffusion rate of Cu in steel. From this plot it can be noticed that the temperature has a much stronger effect on the rate of diffusion of Cu in steel than does the carbon content.

Fig. 9 shows the effect of the carbon content of the steel on both the diffusion coefficient of Cu and the activation energy. From this plot it is clear that as the carbon content increases the diffusion coefficients decrease and the activation energies increase.

4. Conclusions

(1) The thin layer method has been shown to be a successful method to study the diffusion of radioactive copper in steel.

(2) The diffusion coefficient of Cu in steel depends on both the carbon content and temperature. However it was found that the temperature has a much stronger effect than the carbon content of the steel.

(3) The activation energy for diffusion as calculated from the Arrhenius plots depends on the carbon content of the steel. Values of the activation energy increase as the carbon content of the steel increases.

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