

**CHEMICAL DIFFUSION DATA: SOURCES OF DATA, METHODS
OF REPRESENTATION AND THE NEEDS OF UK INDUSTRY**

A T Dinsdale
Centre for Materials Measurement and Technology
National Physical Laboratory, Teddington
Middlesex TW11 0LW

ABSTRACT

Chemical diffusion data provide information about how quickly elements or species migrate along a composition gradient in the direction of chemical equilibrium. This report summarises the sources of chemical diffusion data and their value. Few sources provide a critical analysis of experimental results for a particular system which is what is required before such data can be used with confidence. Chemical diffusion data vary markedly with both temperature and composition. Ways in which these data can be represented mathematically and extrapolated into multicomponent systems are described. Key steps necessary to provide a sound foundation for future modelling of such data are identified. The development of a capability at NPL for the experimental determination of chemical diffusion data is recommended.

© Crown copyright 1997
Reproduced by permission of the Controller of HMSO

ISSN 1361-4061

National Physical Laboratory, Teddington,
Middlesex TW11 0LW, UK

Extracts from this report may be reproduced provided the source is acknowledged.

Approved on behalf of the Managing Director, NPL, by Dr C Lea,
Head of the Centre for Materials Measurement and Technology.

CHEMICAL DIFFUSION DATA: SOURCES OF DATA, METHODS OF REPRESENTATION AND THE NEEDS OF UK INDUSTRY

Introduction

The aim of this document is to provide a review of the sources available for data for chemical diffusion in alloy systems, methods for their presentation as functions of temperature and composition and how the available data correspond to the present needs of UK industry. Sources of data for slags and molten salts are also included. In practice, for alloy systems, diffusion data are required only for crystalline phases, since diffusion in the liquid phase is of the order of 10^3 times faster. Consequently, for practical purposes, it is often possible to assume that the liquid phase is homogeneous. This review is concerned solely with volume diffusion. Grain boundary diffusion, while important, is outside the scope of the present work. The various ways in which diffusion properties can be measured is covered in a separate report by Monaghan (97mon).

Sources of volume diffusion data

Volume diffusion data have been studied since about 1940 and results have appeared in a variety of journals since then. No one journal appears to have acted as a focus for publications in this field. More recently, however, the journal "Diffusion and Defect Data", which has two parts concerned with "Defect and Diffusion Form" and "Solid State Phenomena", provides a useful survey and abstracts of recently published work on the measurement and analysis of chemical diffusion coefficients. Eg Volume 140 (1996), Pt A. Abstracts by D J Fisher.

There are reviews of data for specific classes of materials of industrial interest. For example there is fairly good coverage of diffusion data for copper based systems (73but/man, 74but/man, 75but/man, 76but/man, 77but/man1, 77but/man2, 81but). This formed part of a wider NBS project which collected papers and reports on chemical diffusion coefficients for alloy systems up to 1982 when the project closed. The collection of references still exists and may still be accessible (97man). The published reviews of data are extremely valuable although they do not provide critically assessed recommended values.

Oikawa has provide a summary of self diffusion in solid iron (82oik1), of diffusion of substitutional elements in infinite dilution in iron (82oik2) and for more concentrated solutions (83oik). The particular importance of Oikawa's work is that it has provided a critical analysis of the experimental data and recommended values to be used. Iijima and Hirano (92iij/hir) have more recently reviewed diffusion data for pure iron, iron-based alloys,

stainless steels, pure nickel and nickel-based alloys although the authors did not recommend any specific data

There are also more general compilations of experimental data:

The Metals Reference Book (76smi/bra) and the Landolt-Börnstein volume number 26 (90meh) provide good background descriptions of diffusion coefficients in crystalline metals and various methods for their measurement. They also give comprehensive tables of

- a) Self diffusion coefficients in solid elements modelled according to a simple Arrhenius type relationship.
- b) Tracer impurity diffusion coefficients for experimental diffusion of various isotopes in dilute solution in various metals
- c) Tracer diffusion coefficients in homogeneous alloys for a variety of systems
- d) Chemical diffusion coefficients for a variety of systems

In neither sets of tables have the values been critically assessed - the published tables simply reflect the data given in the original literature. These reviews also indicate where gaps exist in available data. Experimental data available for ternary and high order systems are fairly sparse, most of the attention seems to be devoted to steel systems. There seems to be lack of data for binary and multicomponent nickel based superalloys and aluminium alloys.

More recently Ågren, Jönsson and colleagues (91liu/hög, 92ågr, 94jön1, 94jön2, 95jön) have critically assessed all volume diffusion data (eg tracer diffusion, chemical diffusion) for Cr-Fe-Ni-C steels and provided a comprehensive dataset valid over a wide range of temperatures and compositions. Similar work is also in progress on superalloys (96eng, 96eng/ågr).

Reviews of diffusion data for molten salt systems (82jan/ban) and slags (95mil) are also available.

Modelling of Chemical Diffusion Data

The subject area of chemical diffusion can cause a great deal of confusion - there are several different physical properties that are related to one another but unfortunately given very similar or even identical names.

From the perspective of use of chemical diffusion data the most important property is the chemical diffusion coefficient which relates the rate at which species diffuse to composition gradients within the material. Chemical diffusion coefficients vary appreciably with both temperature and composition. Figure 1 shows the variation of the chemical diffusion

coefficient for a range of Cu-Ni alloys as function of the reciprocal temperature.

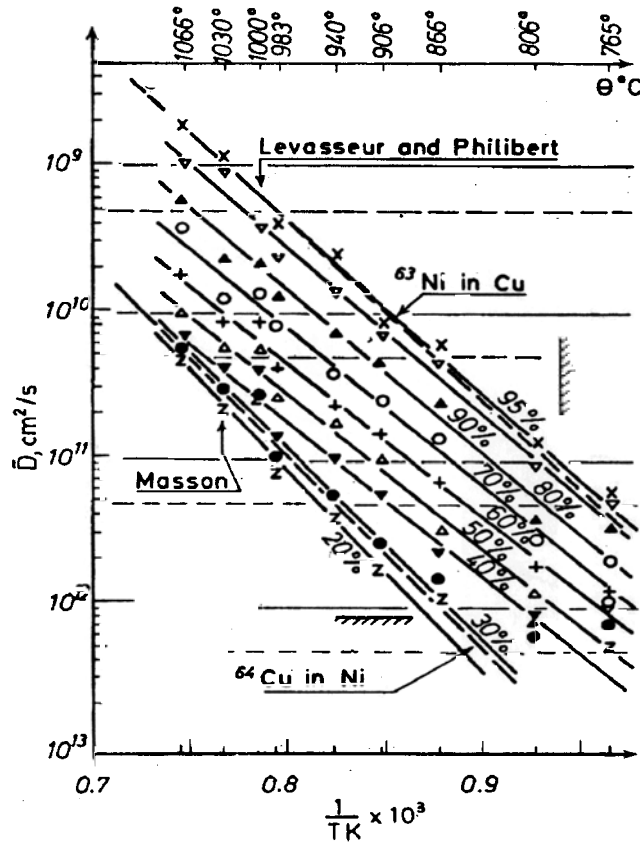


Figure 1 Variation of chemical diffusion coefficient for Cu-Ni alloys as a function of the reciprocal temperature (76smi/bra)

This is typical of the relationship between any of the different types of diffusion coefficient and temperature which, in the absence of special effects such as a magnetism, can be represented by the general formula

$$D = A \exp\left(\frac{-Q}{RT}\right)$$

where D is the diffusion coefficient, Q is thought of as some activation energy, A often termed the 'frequency factor' and R is the gas constant. The temperature T is expressed in Kelvins. The effect of magnetism has been discussed by Ågren (92ågr)

The variation of the chemical diffusion coefficient with composition for some systems eg Co-Ni is fairly simple as shown in Figure 2 for a number of temperatures.

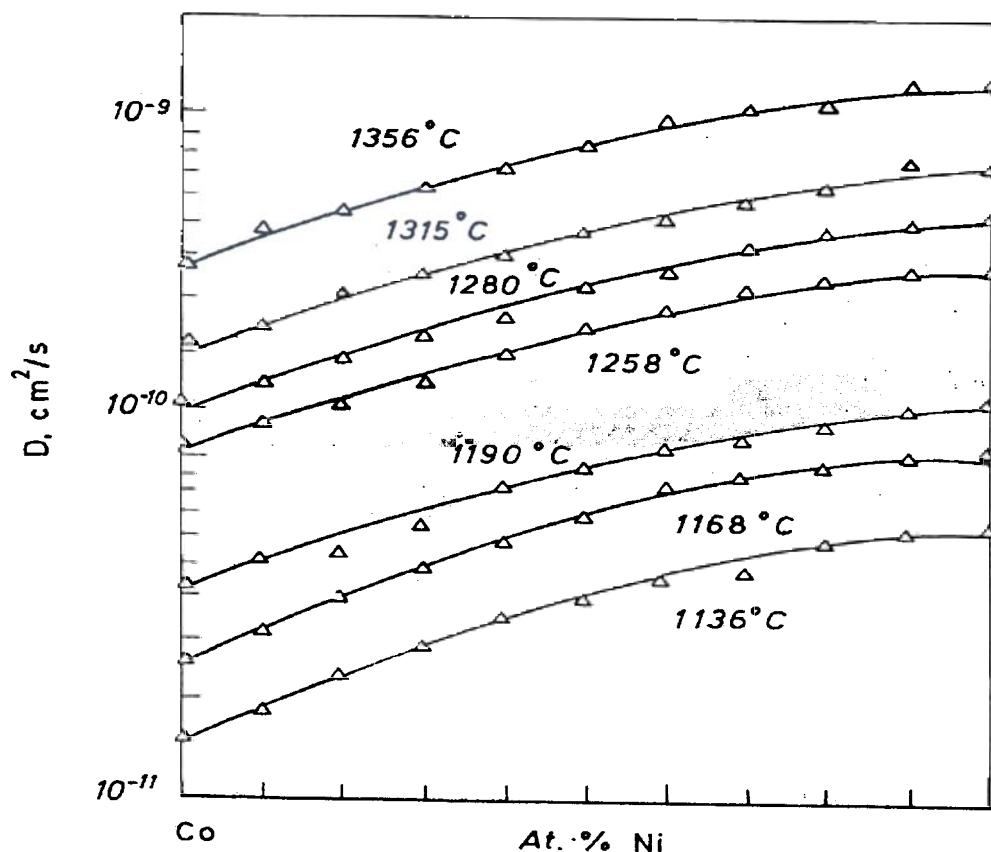


Figure 2 Dependence of the chemical diffusion coefficient for Co-Ni alloys on composition for a number of temperatures (76smi/bra). The right axis of the diagram represents pure nickel.

Here both elements for these temperatures have the same structure and there is very little chemical interaction between them. For other systems where there is some strong chemical interaction between the elements the variation of the chemical diffusion coefficient is not as simple. Figure 3 shows the equivalent diagram for the Al-Ni system. Here there is a strong tendency towards chemical ordering which results in a marked change in the chemical diffusion coefficients in the region of the equiatomic composition. For more complex types of crystal structure diffusion will also be anisotropic i.e. it will depend on the direction within the crystal lattice. This complex area is outside the scope of this present report.

If, for a given temperature, each element is stable in a different crystal structure there would need to be two distinct curves, one for each structure. For regions of composition where a given phase is not stable the chemical diffusion coefficients cannot be measured although it would still be helpful for modelling purposes to extrapolate the experimental data back to the pure elements. An example of this is shown schematically in Figure 4 for Cr-Fe alloys.

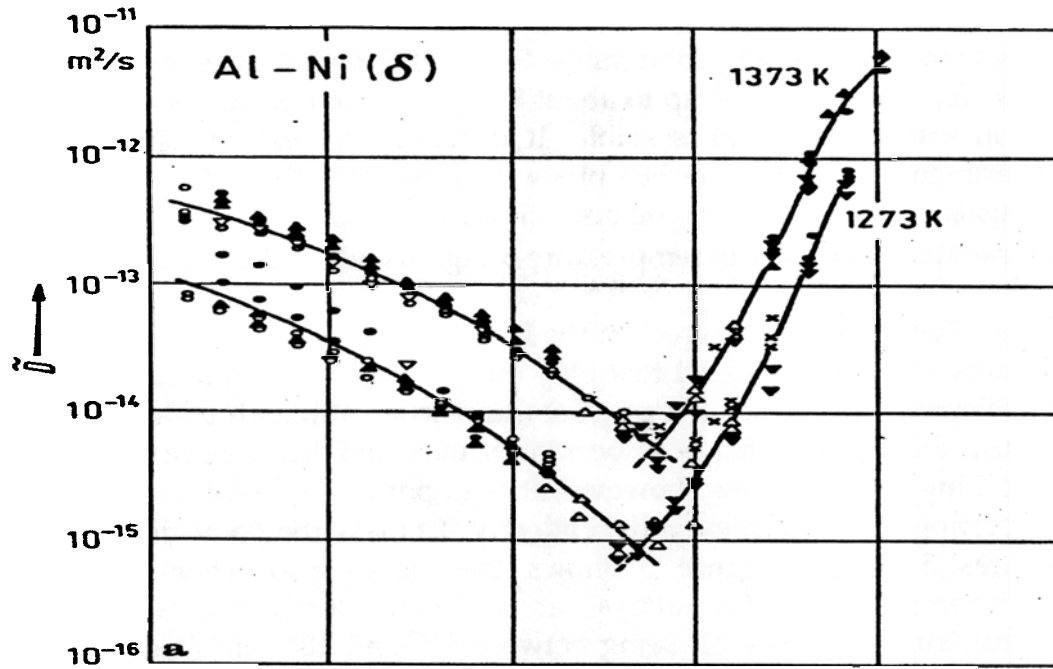


Figure 3 Chemical diffusion coefficient for Al-Ni alloys as a function of composition (90meh). The abscissa represents compositions from 35 to 60 at % Ni.

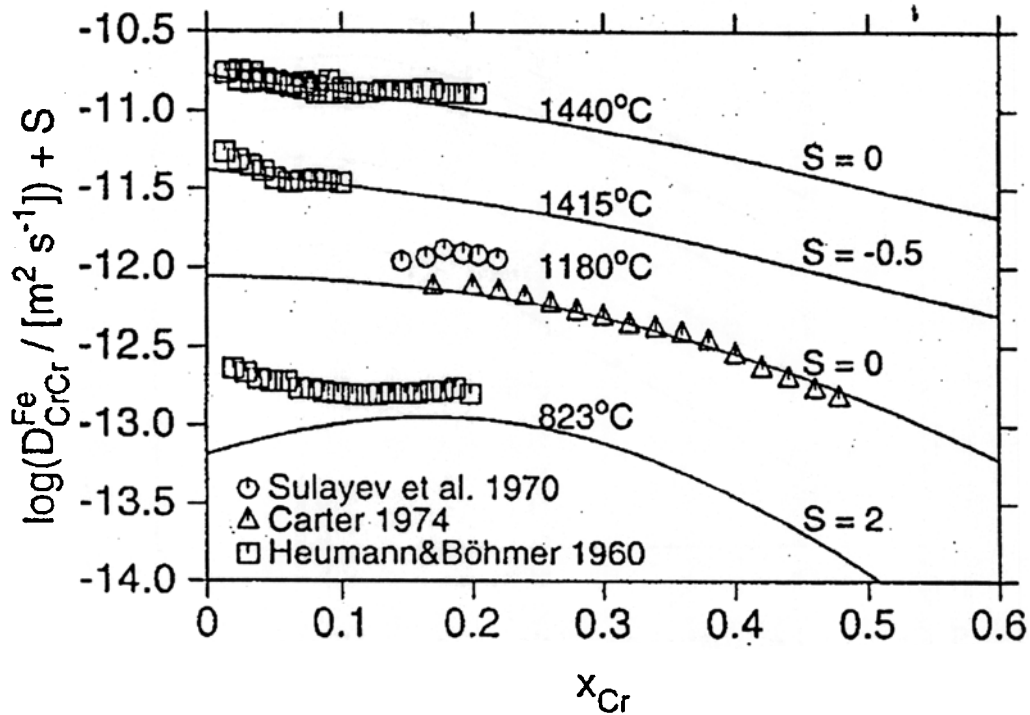


Figure 4 Variation of chemical diffusion coefficient with composition for bcc Cr-Fe alloys (94jön2). Note that the data for 1180°C have been extrapolated to pure iron which is metastable at this temperature.

For 1440°C, 1415°C and 823°C Fe-Cr alloys are stable in the bcc structure across the whole composition range. For 1180°C the bcc structure is the stable phase for concentrations up to about 85%Fe. For compositions close to Fe the fcc structure (austenite) is stable. It is reasonably easy to extrapolate the experimental data for the bcc phase back to pure Fe. This should also be consistent with an extrapolation of data for pure Fe from the higher temperature δ and lower temperature α regions where the bcc phase is stable.

So far discussion has centred on the chemical diffusion coefficient for binary systems and it has implied that only one coefficient is required even though two elements are present. In practice this is true - although both elements will diffuse differently what is important is their composite behaviour. From a modelling point of view, however, it is important to consider the diffusion properties of each element independently. To make the point clearer consider Figures 5 and 6. Figure 5 shows the variation of chemical diffusion coefficients for Fe-Ni alloys at different temperatures, the value corresponding to pure Ni being between 10^{-9} and 10^{-11} cm²/s depending on the temperature.

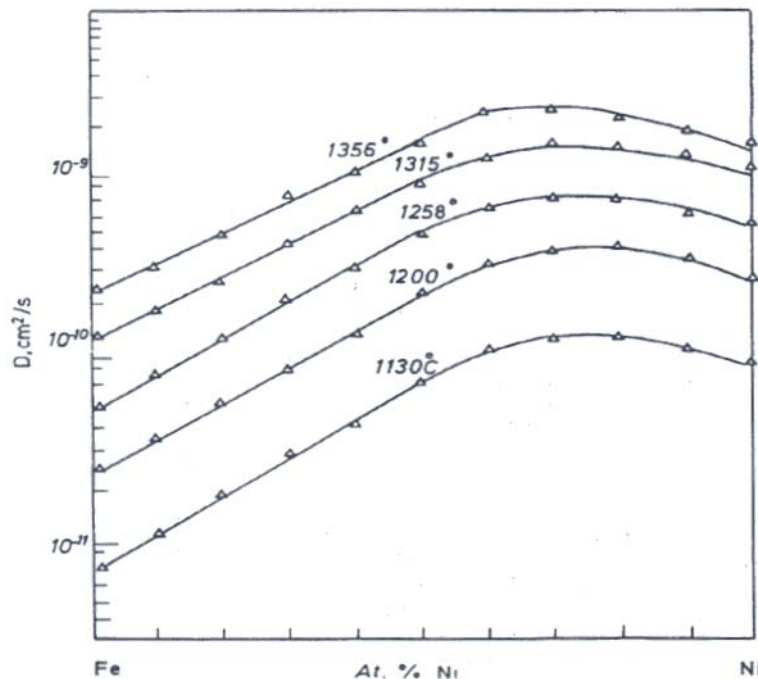


Figure 5 Chemical diffusion coefficients for Fe-Ni alloys (76smi/bra). Note that the values are of the order of 10^{-10} cm²/s.

Figure 6 shows the variation of chemical diffusion coefficients for Ni-Pt alloys over a similar temperature range. Here for pure Ni the values range from 10^{-22} to 10^{-26} cm²/s. From this one can see that the chemical diffusion coefficient corresponding to pure Ni depends on the particular system under

consideration. It is desirable to base any general model for chemical diffusion on properties that are unique for each element for a given temperature.

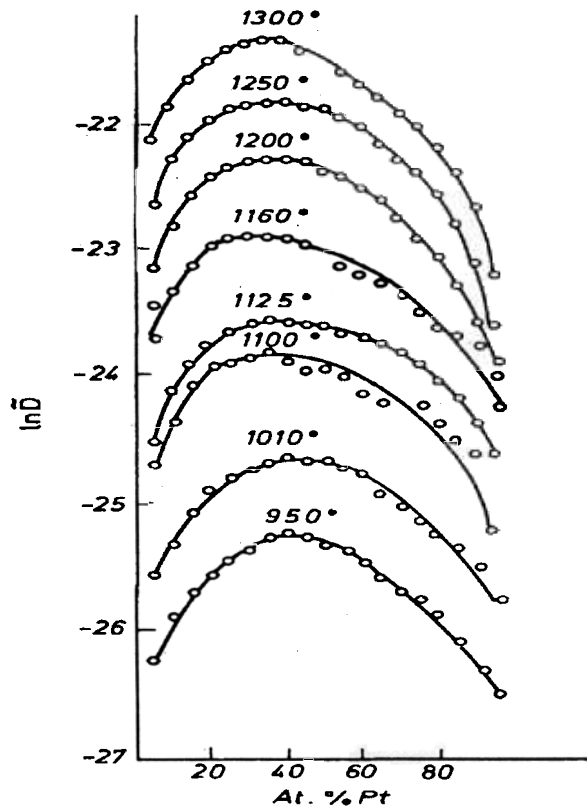


Figure 6 Chemical diffusion data for Ni-Pt alloys. Note that the values are of the order of 10^{-24} cm²/s (76smi/bra).

The chemical diffusion coefficient for a binary system can be split into separate parts - each relating to an individual element - according to the equation:

$$\bar{D} = x_A D_B + x_B D_A$$

where $\bar{D}$ is the chemical diffusion coefficient, x_A and x_B are the mole fractions of components A and B respectively and D_A and D_B are called the intrinsic diffusion coefficients of A and B respectively and can in principle be measured by observing the diffusion relative to inert markers incorporated into the sample under study. Figure 7 illustrates how these intrinsic diffusion coefficients may vary with composition and their relation to the chemical diffusion coefficient.

The obvious point to note from Figure 7 is that at the edges of the diagram ie when x_A or x_B is equal to zero, the chemical diffusion coefficient becomes equal to the intrinsic diffusion coefficient of the solute eg for pure A the chemical diffusion coefficient becomes equal to the intrinsic diffusion coefficient of B. It follows that for these compositions the intrinsic diffusion

coefficient of the solvent does not contribute to the chemical diffusion coefficient. Referring back to Figures 5 and 6 it is now apparent the marked difference in the chemical diffusion coefficient corresponding to a composition of pure Ni for the Fe-Ni and Ni-Pt systems reflects the different values for the intrinsic diffusion coefficient of Fe and Pt in pure Ni.

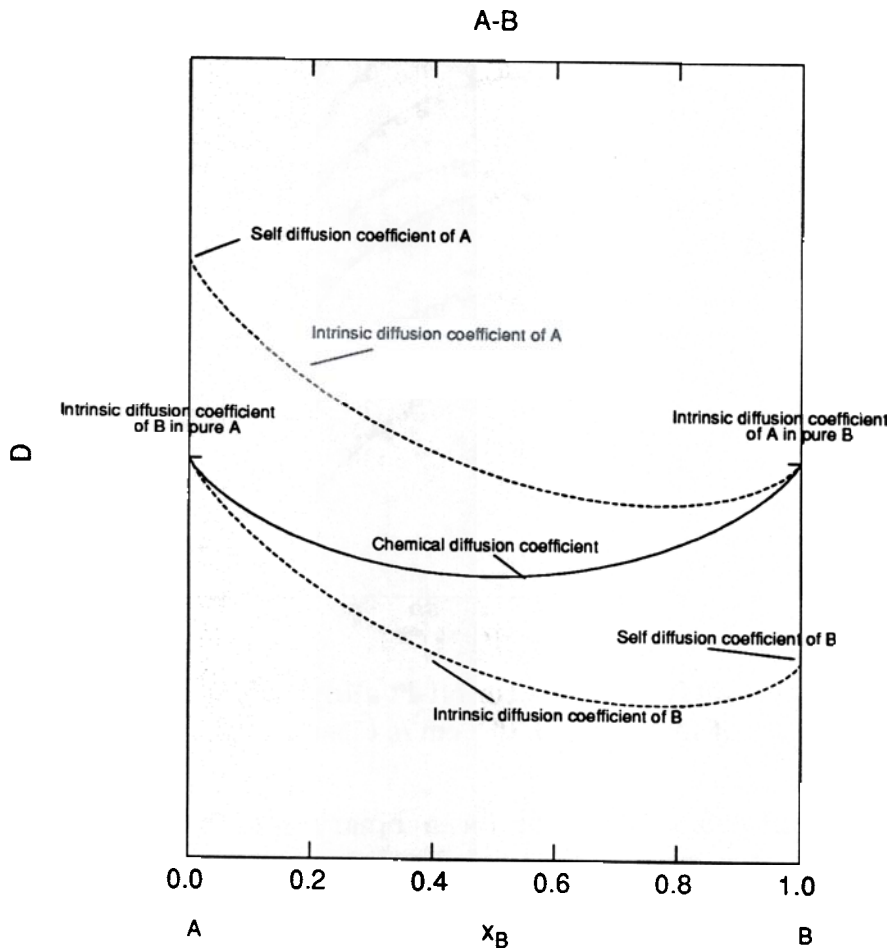


Figure 7 Schematic diagram to illustrate the relationship between different diffusion coefficients

These four limiting values for the intrinsic diffusion coefficients as the mole fraction of one element becomes zero correspond closely to limiting values for yet another type of diffusion coefficient - the so-called tracer diffusion coefficient. Tracer diffusion coefficients D_A^* and D_B^* can be determined experimentally through observing the diffusion of radioactive tracer atoms in a homogeneous material. Since in this case there is no composition gradient the results obtained in this way differ fundamentally from intrinsic diffusion coefficients. For the limiting composition regions, however, the tracer diffusion coefficients become identical to the intrinsic diffusion coefficients. The diffusion of atoms of an element in a matrix of that same element is called self diffusion. The diffusion of atoms of one element in very dilute solution in another element is called tracer impurity diffusion. In general for

any alloy the tracer diffusion coefficients and intrinsic diffusion coefficients are related through the so-called Darken equation:

$$D_A = D_A^* \phi$$

$$D_B = D_B^* \phi$$

where ϕ is called the thermodynamic factor given by

$$\phi = 1 + \frac{\partial \ln \gamma_i}{\partial \ln x_i}$$

where γ_i is the activity coefficient of i.

This relationship shows that, if a description of the thermodynamic properties of a given phase is available the tracer diffusion coefficients, the intrinsic diffusion coefficients and the chemical diffusion coefficients can all be related to one another.

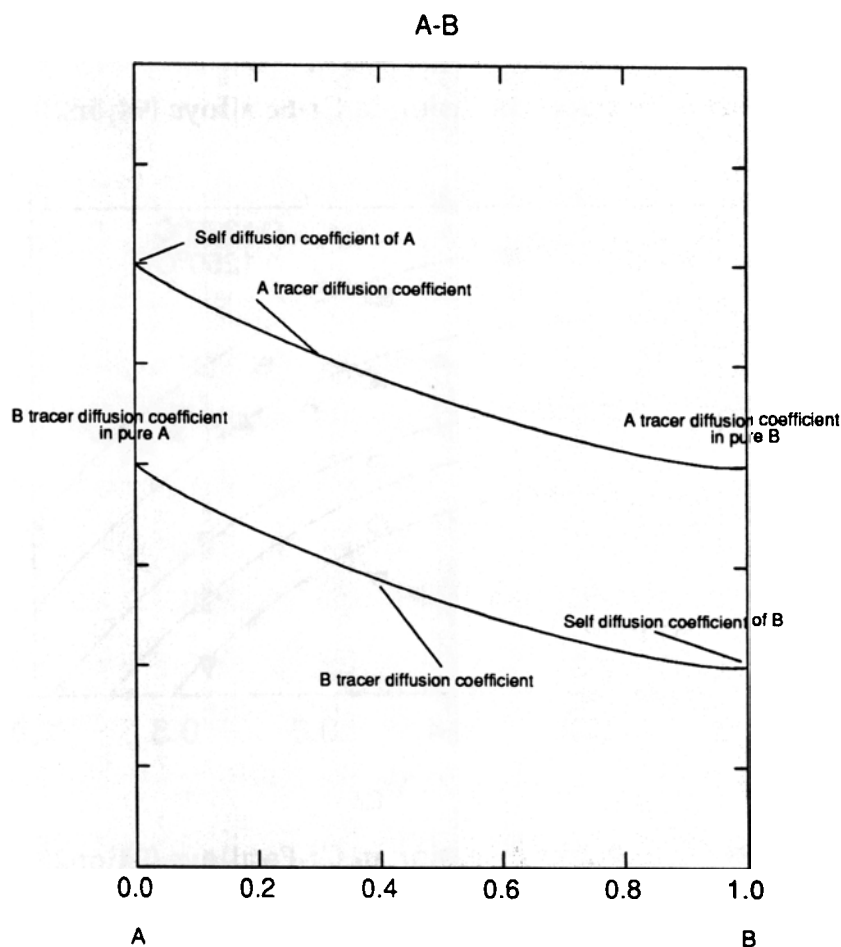


Figure 8 Schematic diagram to illustrate the variation of tracer diffusion coefficients with composition. This should be compared with Figure 9

Figure 8 shows schematically how tracer diffusion coefficients may vary with composition and should be compared with Figure 7.

Figures 9 and 10 show how tracer diffusion coefficients vary with composition for Cr-Fe alloys (94jön2).

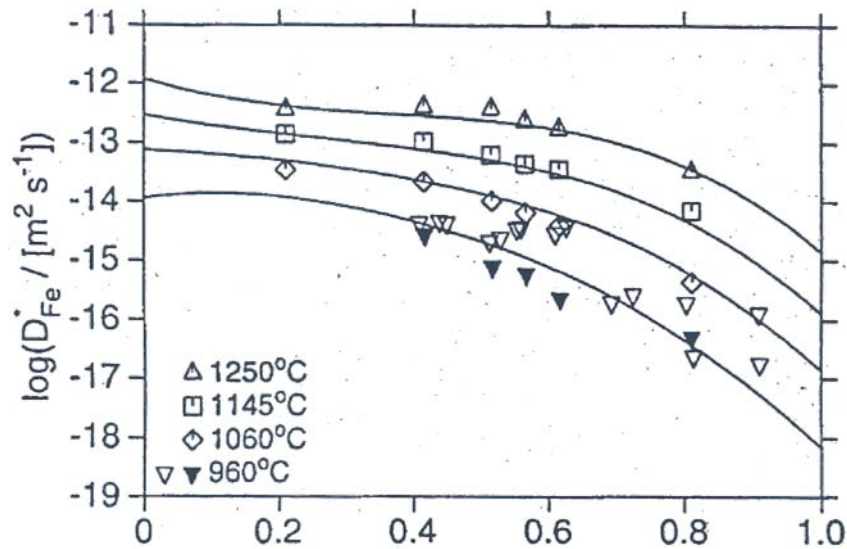


Figure 9 Fe tracer diffusion in Cr-Fe alloys (94jön2)

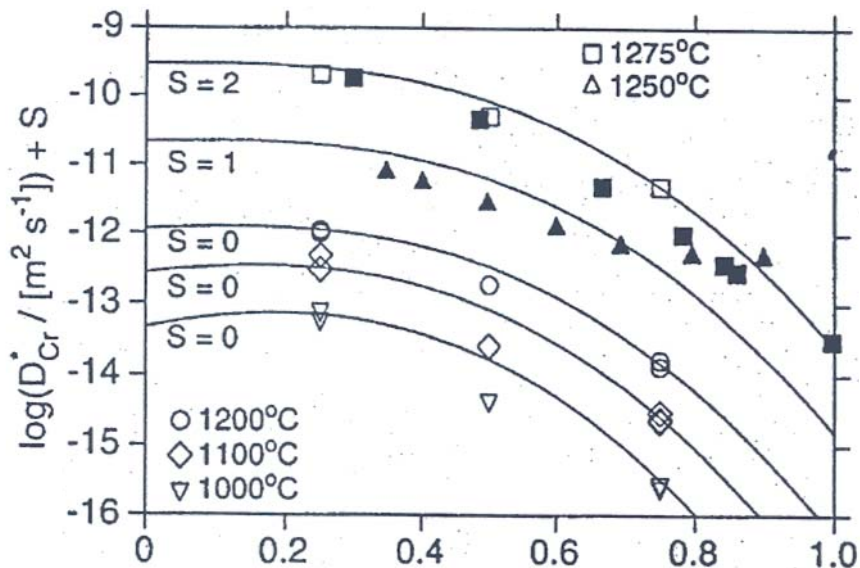


Figure 10 Cr tracer diffusion in Cr-Fe alloys (94jön2)

The tracer diffusion coefficients can in turn be related to the atomic mobility of the elements eg

$$D_B^* = R T M_B$$

where the mobility M_B can be represented as a function of temperature by an Arrhenius type equation:

$$M_B = \frac{M_B^*}{RT} \exp\left(\frac{-Q_B}{RT}\right)$$

where, again, M_B^* is a frequency factor, Q_B an activation energy and R the gas constant. In order to model the variation of chemical diffusion as a function of composition the activation energy Q_B can be expressed in terms of some Redlich Kister type power series expression as demonstrated by Andersson and Ågren (92and/agr): eg

$$Q_B = x_A Q_B^A + x_B Q_B^B + x_A x_B \sum_{i=0}^i Q_B^{A,B} (x_A - x_B)^i$$

where Q_B^A and Q_B^B represent the activation energies associated with tracer impurity diffusion and self diffusion respectively while the parameters $Q_B^{A,B}$ are coefficients to represent the variation of the interaction energy with composition.

The frequency factor M_B^* will also vary with composition. Here, however, the values could be expected to vary in a non-linear way. Jönsson (94jön2) suggested that an appropriate way to express this variation would be through

$$M_B^* = \exp(\theta_B)$$

θ_B would then be described using a similar expression to that used for Q_B .

Certain elements, eg C, dissolve interstitially within metals. Modelling of diffusion must take into account the nature of the solution. This subject has been discussed by Andersson and Ågren (92and/ågr).

Multicomponent systems

The representation of mobility data for binary systems can be extended easily to multicomponent systems. However their transformation to chemical diffusion coefficients is a little more complex. For a particular composition and temperature in a binary system there is only one independent composition gradient ie only a single chemical diffusion coefficient is required and this can be modelled in terms of two intrinsic diffusion coefficients or two mobilities. For a ternary or multicomponent system, however, there will need to be a diffusion coefficient for each species along

each composition gradient. Fortunately because the sum of the composition gradients for a particular species must equal zero one of these may be eliminated. By assigning one gradient to act as a reference it is possible to define diffusion in the phase in terms of $n-1$ independent diffusion coefficients for each of the n species.

If D_{ij} is the intrinsic diffusion coefficient of species i along the composition gradient of species j and the gradient in composition $\partial c_n / \partial x$ chosen as the reference gradient it is possible to define so called partial diffusion coefficients from the relationship

$$D_{ij}^n = D_{ij} - D_{in}$$

These partial diffusion coefficients can also be predicted from use of the mobilities provided their variation is known as a function of composition and the equivalent thermodynamic description is available. Since the mobilities (and tracer diffusion coefficients) are not dependent on composition gradients only n are required to be defined for an n component system. By making the appropriate conversion using the thermodynamic data these can be used to derive the $n(n-1)$ chemical diffusion coefficients required. The approach has been used with some success at the Royal Institute of Technology, Stockholm which has begun the development of a mobility database (94jon1, 94jon2, 95jon, 96eng/agr).

Use of chemical diffusion data

Diffusion of material at a fixed temperature along a composition gradient is governed by Fick's first law (1855fic) which relates the flux J_i of a diffusing species i to the concentration gradient.

$$J = - D \frac{\partial c_i}{\partial x}$$

The concentration c_i is the amount of diffusing substance per unit volume and unit concentration gradient along a particular defined axis designated as x . The chemical diffusion must be referred to an appropriate frame of reference. From an experimental point of view the most useful frame of reference is the volume fixed or Mantano frame of reference. For this case the flux J_i can be defined as the amount of a diffusing substance i that passes per unit time and unit area of a plane perpendicular to the x axis.

There is also a mass balance constraint, the so-called continuity equation that relates the change in concentration with time to the variation of flux with distance.

$$\frac{\partial c_i}{\partial t} = \frac{\partial}{\partial x} (-J_i)$$

With the previous equation this gives, what is sometimes called Fick's second law.

$$\frac{\partial c_i}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial c_i}{\partial x} \right)$$

By assuming that all the substitution species have the same partial molar volumes it is possible to obtain for the general multicomponent case using the partial diffusion coefficients described in the last section:

$$J_i = - \sum_{j=1}^{n-1} D_{ij}^n \frac{\partial c_j}{\partial x}$$

For the case where the D_{ij}^n are assumed to be constant as a function of composition it is possible to derive analytical expressions (71gup/coo) to solve the diffusion equations. In other cases analytical methods are required such as those suggested by Agren (82agr).

So far it has been assumed that species diffuse along a composition gradient. In the general sense species will diffuse in a direction that will lead to a lowering of the Gibbs energy. Diffusion along a composition gradient will lead to an increase in the configurational entropy. However in cases where the species interact these interactions may cause diffusion to occur in other less obvious ways eg Darken's so-called uphill diffusion. The thermodynamic aspects were introduced by Onsager who also generalised their treatment for a multicomponent system (31ons1, 31ons2) by relating the flux to the thermodynamic properties of the material.

Discussion thus far has been concerned with crystalline phases which are stable over a wide composition range such that the chemical potentials can be defined as a function of composition. Certain compound phases may exist over very limited composition ranges which prevent the definition of the chemical potential in this way. The handling of data for these compounds has been described by Gulpen et al. (94gul/kod).

Current use of chemical diffusion data

Chemical diffusion data are used essentially by individuals or organisations interested in modelling or controlling processes. The largest single interest in the UK seems to be associated with modelling of casting and solidification and the prediction of the phases formed and their compositions depending on the process variables such as the cooling rate or the rate at which heat is

extracted from the melt. Modelling of back diffusion ie within material already solidified is a key requirement. Such modelling requires access to thermodynamic data, chemical diffusion data and fairly sophisticated software. The alloys concerned (eg steels, aluminium base, copper based, nickel base superalloys) generally contain a large number of components. While thermodynamic data are required for both liquid and crystalline phases, diffusion data in practice are required only for the crystalline phases.

In related fields, diffusion data are also used in modelling solid state phase transformations and reactions. One particular example is associated with the formation of carbides, their precipitation or dissolution in steels and modelling the effect of heat treatment and homogenisation. Development of diffusion databases would allow the prediction of TTT (time-temperature-transformation) and CTT (composition-temperature-transformation) diagrams.

The field of corrosion would also benefit from access to chemical diffusion data eg in the field of nitrocarburising where C and N are added simultaneously to a steel surface at low temperatures. A full understanding and control of this process could only be obtained through a combined thermodynamic and diffusion calculation.

At present chemical diffusion data tend to be sparse even for binary systems. It is the norm for users of such data to adopt an experimental, unassessed value from the literature and assume that it has no composition or even temperature dependence and that cross terms are unimportant (ie the diffusion of a species along the composition gradient of another species can be neglected). In such cases a value of the chemical diffusion coefficient within a factor of 2 or 3 is often adequate. In some cases the chemical diffusion coefficient may be used as a adjustable parameter and varied in order to achieve agreement between a model and experimental observations.

Critically assessed thermodynamic data are slowly becoming available largely through international collaborative projects or projects where the cost of the database development is shared between a number of sponsors. The availability of databases for thermodynamic data is dealt with in a companion report (97din/dav). Equivalent databases need to be developed for chemical diffusion data to enable calculations to be undertaken for commercial alloys. A prototype mobility database is under development at the Royal Institute of Technology in Stockholm. Such databases would enable chemical diffusion data to be represented as functions of temperature and composition and to enable predictions to be made of behaviour in more complicated systems where experimental data are lacking. It is necessary to develop these databases in collaboration with other organisations, not necessarily just within the UK, on a precompetitive basis in order to increase the speed of database development. The first steps should be:

- Development of critically assessed standard reference data for self diffusion of the elements of interest.
- Development of critically assessed data for tracer impurity diffusion coefficients ie for a dilute solution of one element in another.
- Critical assessment of data for key systems for industrially important materials. The procedure would be to derive data for binary systems, then to use phenomenological models to extrapolate these data into ternary and multicomponent systems introducing ternary parameters where necessary.

It is also desirable that NPL should develop its own capability to measure chemical diffusion coefficients. This would provide basic information required for the critical assessment of data for key systems where no data currently exists or for which there is uncertainty.

Recommendations

- Development of a critically assessed database for chemical diffusion data.
- Development of software to enable these data to be used for modelling solidification and phase transformation phenomena.
- Development of experimental capability to fill gaps in diffusion data in the literature.

References

- 1855fic A Fick; Annalen der Physik und Chemie, 1855, 94, 59-86
- 31ons1 L Onsager; Phys. Rev., 1931, 37, 405-26
- 31ons2 L Onsager, Phys. Rev., 1931, 38, 2265-79
- 71gup/coo P K Gupta, A R Cooper, Physica, 1971, 54, 39-59
- 73but/man D B Butrymowicz, J R Manning, M E Read, J. Phys. Chem. Ref. Data, 1973, 2(3), 643-655. "Diffusion in copper and copper alloys, Part I: Volume and surface self diffusion in copper"
- 74but/man D B Butrymowicz, J R Manning, M E Read, J. Phys. Chem. Ref. Data, 1974, 3(2), 527-602. "Diffusion in copper and copper alloys, Part II: Copper-Silver and Copper-Gold systems"
- 75but/man D B Butrymowicz, J R Manning, M E Read, J. Phys. Chem. Ref. Data, 1975, 4(1), 177-249. "Diffusion in copper and copper alloys, Part III: Groups IA, IIA, IIB, IVB, VB, VIB and VIIB"
- 76but/man D B Butrymowicz, J R Manning, M E Read, J. Phys. Chem. Ref. Data, 1976, 5(1), 103-200. "Diffusion in copper and copper alloys, Part IV: Group VIII"
- 76smi/bra The Metals Reference Book, 5th edition, ed C J Smithells and E A Brandes, publ. Butterworths
- 77but/man1 D B Butrymowicz, J R Manning, M E Read, "Diffusion rate data and mass transport phenomena for copper systems", INCRA Monograph V in the series "The metallurgy of Copper", 1977

- 77but/man2 D B Butrymowicz, J R Manning, M E Read, J. Phys. Chem. Ref. Data, 1977, 6(1), 1-50. "Diffusion in copper and copper alloys, Part V: Diffusion in systems involving elements of Group VA"
- 81but D B Butrymowicz, "Diffusion rate data and mass transport phenomena for copper systems", INCRA Monograph VII in the series "The metallurgy of Copper", 1981
- 82ågr J Ågren, J. Phys. Chem. Solids, 1982, 43, 385-91
- 82jan/ban G J Janz, N P Bansal, J. Phys. Chem. Ref. Data, 1982, 11(3), 505-693. "Molten Salts data: Diffusion coefficients in single and multicomponent salt systems"
- 82oik1 H Oikawa, Technology Reports, Tohoku Univ., 1982, 47(1), 67-77. "Lattice self-diffusion in solid iron: a critical review"
- 82oik2 H Oikawa, Technology Reports, Tohoku Univ., 1982, 47(2), 215-224. "Review on lattice diffusion of substitutional impurities in iron. A summary report"
- 83oik H Oikawa, Technology Reports, Tohoku Univ., 1983, 48(1), 7-77. "Lattice diffusion of substitutional elements in iron and iron-base solid solutions. A critical review"
- 90meh Landolt Börnstein New Series, Volume 26, "Diffusion in solid metals and alloys", 1990, publ. Springer-Verlag, ed. H Mehrer.
- 91liu/hög Zi-Kui Liu, L Höglund, B Jönsson, J Ågren, Metall. Trans. A, 1991, 22A, 1745-1752. "An experimental and theoretical study of cementite dissolution in an Fe-Cr-C alloy"
- 92iij/hir Y Iijima, K Hirano, in Diffusion Processes in Nuclear Materials, ed R P Agarwala, 1992. Publ. Elsevier Science publishers BV, 169-200. "Diffusion in iron, steels and some nickel alloys"
- 92ågr J Ågren, ISIJ International, 1992, 32(3), 291-6. "Computer simulations of diffusional reactions in complex steels"
- 92and/ågr J-O Andersson, J Ågren, J. Appl. Phys., 1992, 72, 1350-5
- 94gul/kod J H Gulpen, A A Kodentsov, F J J van Loo, Proc. Symp. "Applications of Thermodynamics in the synthesis and processing of materials", Rosemont, Illinois, USA, October 2-6, 1994 ed. P Nash and B Sundman, publ. TMS
- 94jön1 B Jönsson, Z. Metallkde, 1994, 85, 498-501
- 94jön2 B Jönsson, Z. Metallkde, 1994, 85, 502-9
- 95jön B Jönsson, ISIJ International, 1995, 35, 1415-21
- 95mil K C Mills, in Slag Atlas 2nd edition, VDEh, 1995, p541-556 "Diffusion coefficients in molten slags"
- 96eng A Engström, Thesis Royal Institute of Technology, Stockholm, 1996. "Long range diffusion and microstructural evolution in multiphase alloys"
- 96eng/ågr A Engström, J Ågren, Z. Metallkde, 1996, 87, 2. "Assessment of diffusional mobilities in face-centered cubic Ni-Cr-Al alloys"
- 97din/dav A T Dinsdale, R H Davies, T I Barry NPL Report CMMT(A)74, July 1997.
- 97man J R Manning, Private communication, 1997
- 97mon B Monaghan, NPL Report CMMT(A)54, July 1997.