Chapter 10

Summary and future work

Following an extensive review of the work done on the topic, it can be said with certainty that precipitation phenomena in austenitic stainless steels are complex, and that controversies persists in many cases.

A part of this work was concerned with the microstructural evolution of a newly designed austenitic stainless steel named NF709, with a particular attention to phases which may be detrimental to long-term creep properties. In this regard, results obtained during this work indicate that the detrimental role of σ-phase is not systematic, as evidence is given that it has little effect on the ductility. It is also shown that significant differences in the precipitation sequences can appear from apparently similar compositions. Furthermore, by combining observations from the literature and the detection of Cr_3Ni_2SiN the role of nitrogen as a stabiliser for the η-structure can be clarified.

Of great interest is also the ability to predict the microstructural evolution of these steels. Based on previous work by Robson and Bhadeshia, and Fujita and Bhadeshia, a model has been created which makes full use of modern thermodynamic calculation tools. This model corrects approximations made necessary when using stand-alone programs, in particular, it is shown that using either the equilibrium tie-line, or the one corresponding to a zero gradient of carbon, is incorrect and does not lead to satisfactory predictions of the growth rate. The problem is only correctly solved when addressing it in terms of activities of the components rather than concentration. Also, the issue of capillarity in multicomponent systems has been examined, and earlier approaches have been corrected. A method has been designed which allows to tackle the problem through modification of the SGTE databases so that capillarity corrections can be calculated directly with MT-

DATA. With the program written so as to avoid too specific solutions, it is hoped that its scope of use will extend beyond austenitic stainless steels in future works.

However, for various reasons, this still has to be considered as a semi-quantitative approach. First, there is a serious lack in available thermodynamic data on phases that are commonly encountered in modern grades of heat-resistant austenitic stainless steels, which strongly limits the number of systems in which meaningful predictions can be made. Furthermore, the model still relies on the mean-field approximation. It is certainly a worthy challenge to overcome this so as to account for localised interactions, or grain-boundary and intragranular precipitation separately. Finally, fundamental reasons have been given which justify a re-examination of the way nucleation theory is used in multicomponent systems, so as to improve the prediction ability of the classical theory.

Given the difficulties in predicting quantitatively the precipitation reactions, it is yet too early to use these calculations as inputs in the further step which is to estimate the mechanical properties. It is clear that a meaningful model based on the precipitation state must include feature such as location, as, for example, grain boundary and intragranular precipitates are known to have different influences, and distribution, as a same phase finely dispersed or present as coarse particles also has different effects.

However, when using powerful empirical methods such as neural network modelling, these difficulties can be avoided; variables such as composition and test conditions can be used directly. With the use of creep data collected from a number of sources, such models have been built to estimate the creep strength and creep life of austenitic stainless steels. Predictions made with these models have been compared to known trends, and shown to grasp properly interactions between different input variables and to be superior to conventional extrapolation methods. It is also interesting to note that the use of physically relevant variables significantly improved the models; for example, the logarithm of time was used rather than time and a variable relevant for the estimation of the quantity of fine MX precipitates was added. This justifies the hope that future models, which may use predicted volume fractions and locations of precipitates as inputs, could help confirming or understanding the role held by the different precipitate phases in determining the creep strength of austenitic stainless steels.

APPENDIX ONE

MAP_STEEL_CREEP_LIFE_AUSTENITIC

This appendix presents the model described in chapter 9 and associated documentation following the MAP format, http://www.msm.cam.ac.uk/map/mapmain.html.

1 Provenance of Source Code

Thomas Sourmail
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Cambridge, CB2 3QZ U.K.

The neural network program was produced by:
David MacKay,
Cavendish Laboratory,
University of Cambridge,
Madingley Road,
Cambridge, CB3 0HE, U.K.

Added to MAP: June 2001.

2 Purpose

A program for the estimation of the creep life of austenitic stainless steels as a function of elemental composition, test conditions and solution treatment.

3 Specification

Language: C
Product Form: Source Code
Operating System: tested on Solaris, SGI and Linux. Can be compiled on most UNIX systems.

4 Description

MAP_STEEL_CREEP_LIFE_AUSTENITIC contains the programs which enable the user to estimate the creep life of austenitic stainless steels as a function of chemical composition, solution-treatment temperature, and stress and temperature of the creep test. It makes use of a neural network program called *generate44*, which was developed by David MacKay and is part of the *bigback5* program. The network was trained using a large database of experimental results [1]. 4 different models are provided, which differ from each other by the number of hidden units and by the value of the seed used when training the network. It was found that a more accurate result could be obtained by averaging the results from all models [1]. The programs calculate the results of each model and then combines them, by averaging, to produce a *committee result* and error estimate, as described by MacKay [2].

The source code is accompanied by a program to install the program, which should run on most versions of UNIX. Once uncompressed, and once the 'install' program run, the directory contains:

README

A text file containing step-by-step instructions for running the program, including a list of input variables.

MINMAX

A text file containing the minimum and maximum limits of each input and output variable. This file is used to normalise and unnormalise the input and ouput data.

test.dat

An input file containing the input variables used for predictions.

model.gen

This is a UNIX shell file containing the commands required to run the model. It can be executed by typing 'sh model.gen' at the command prompt. This shell file normalises the input data, executes the neural network program, unnormalises the results and combine them to produce the final *committee* result.

.normalise

Hidden executable file, to normalise the input data.

.generate44

Hidden executable file, for the neural network program. It reads the normalised input file and also uses a configuration file *spec.t* generated by *.generate_spec* and the weight files, located in the subdirectory *c*.

.generate_spec

Hidden executable file, generates the configuration file read by *.generate44*.

.gencom

Hidden executable file, combines the output of the different models in a *committee* result.

.treatout

Unnormalise the results.

SUBDIRECTORY c

_w*f

The weight files of the different models.

***.lu**

Files containing information for calculating the size of the error bars for the different models.

_c*

Files containing information about the perceived significance value [1] for each model.

_R*

Files containing information about the noise, test error and log predictive error [1] for each model.

SUBDIRECTORY d

outran.x A normalised output file which was created during the building of the model. It is accessed by *.generate44*.

SUBDIRECTORY outprdt

out1, out2, *etc.*

The normalised output files for each model.

com.dat

The normalised output file containing the committee results. It is generated by *.gencom*.

5 References

1. Thomas Sourmail, H. K. D. H. Bhadeshia and D. J. C. MacKay, *A neural network model for the creep strength of austenitic stainless steels.*, Materials Science and Technology, *in press.*
2. D. J. C. MacKay, *Mathematical modelling of weld phenomena 3*, eds. H. Cerjak and H. K. D. H. Bhadeshia, Institute of Materials, London (1997) 359, 3. D. J. C. MacKay's website at http://wol.ra.phy.cam.ac.uk/mackay/README.html

6 Input parameters

The input variables are listed in the README file in the corresponding directory. The maximum and minimum values for each variable are given in the file MINMAX.

7 Output parameters

These give the creep life in log h. The output is written in the file result.txt.

Accuracy

A full calculation of the error bar is presented in reference 1.

Program data

See sample file test.dat

Program results

See sample file result.txt

Keywords

Neural networks, creep life, austenitic stainless steels.

APPENDIX TWO

MAP_STEEL_CREEP_STRENGTH_AUSTENITIC

This appendix presents the model described in chapter 9 and associated documentation following the MAP format, http://www.msm.cam.ac.uk/map/mapmain.html.

1 Provenance of Source Code

Thomas Sourmail
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Cambridge, CB2 3QZ U.K.

The neural network program was produced by:
David MacKay,
Cavendish Laboratory,
University of Cambridge,
Madingley Road,
Cambridge, CB3 0HE, U.K.

Added to MAP: June 2001.

2 Purpose

A program for the estimation of the creep strength of austenitic stainless steels as a function of elemental composition, temperature of creep test and required life.

3 Specification

Language: C
Product Form: Source Code
Operating System: tested on Solaris, SGI and Linux. Can be compiled on most UNIX systems.

4 Description

MAP_STEEL_CREEP_STRENGTH_AUSTENITIC contains the programs which enable the user to estimate the creep strength of austenitic stainless steels as a function of chemical composition, temperature of the creep test and required life. It makes use of a neural network program called *generate44*, which was developed by David MacKay and is part of the *bigback5* program. The network was trained using a large database of experimental results [1]. 14 different models are provided, which differ from each other by the number of hidden units and by the value of the seed used when training the network. It was found that a more accurate result could be obtained by averaging the results from all models [1]. The programs calculate the results of each model and then combines them, by averaging, to produce a *committee result* and error estimate, as described by MacKay [2].

The source code is accompanied by a program to install the program, which should run on most versions of UNIX. Once uncompressed, and once the 'install' program run, the directory contains:

README

A text file containing step-by-step instructions for running the program, including a list of input variables.

MINMAX

A text file containing the minimum and maximum limits of each input and output variable. This file is used to normalise and unnormalise the input and ouput data.

test.dat

An input file containing the input variables used for predictions.

model.gen

This is a UNIX shell file containing the commands required to run the model. It can be executed by typing 'sh model.gen' at the command prompt. This shell file normalises the input data, executes the neural network program, unnormalises the results and combine them to produce the final *committee* result.

.normalise

Hidden executable file, to normalise the input data.

.generate44

Hidden executable file, for the neural network program. It reads the normalised input file and also uses a configuration file *spec.t* generated by *.generate_spec* and the weight files, located in the subdirectory *c*.

.generate_spec

Hidden executable file, generates the configuration file read by *.generate44*.

.gencom

Hidden executable file, combines the output of the different models in a *committee* result.

.treatout

Unnormalise the results.

SUBDIRECTORY c

_w*f

The weight files of the different models.

***.lu**

Files containing information for calculating the size of the error bars for the different models.

_c*

Files containing information about the perceived significance value [1] for each model.

_R*

Files containing information about the noise, test error and log predictive error [1] for each model.

SUBDIRECTORY d

outran.x A normalised output file which was created during the building of the model. It is accessed by *.generate44*.

SUBDIRECTORY outprdt

out1, out2, ***etc.***

The normalised output files for each model.

com.dat

The normalised output file containing the committee results. It is generated by *.gencom*.

5 References

1. Thomas Sourmail, H. K. D. H. Bhadeshia and D. J. C. MacKay, *A neural network model for the creep strength of austenitic stainless steels.*, Materials Science and Technology, *in press.*
2. D. J. C. MacKay, *Mathematical modelling of weld phenomena 3*, eds. H. Cerjak and H. K. D. H. Bhadeshia, Institute of Materials, London (1997) 359, 3. D. J. C. MacKay's website at http://wol.ra.phy.cam.ac.uk/mackay/README.html

6 Input parameters

The input variables are listed in the README file in the corresponding directory. The maximum and minimum values for each variable are given in the file MINMAX.

7 Output parameters

These give the creep life in log h. The output is written in the file result.txt.

Accuracy

A full calculation of the error bar is presented in reference 1.

Program data

See sample file test.dat

Program results

See sample file result.txt

Keywords

Neural networks, creep strength, austenitic stainless steels.

APPENDIX THREE

MAP_DATA_MTDATA_CAPILLARITY

This appendix presents the databases created to include capillarity effects in MT-DATA calculations, as decribed in chapter 5 and associated documentation following the MAP format, http://www.msm.cam.ac.uk/map/mapmain.html.

1 Provenance of Source Code

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Phase Transformations and Complex Properties Group,
Department of Materials Science and Metallurgy,
University of Cambridge,
Cambridge, CB2 3QZ U.K.

The original data were from the SGTE (Scientific Group Thermodata Europe) databases included with MT-DATA,
National Physical Laboratory,
Teddington,
Middlesex,
TW11 0LW, U.K.

Added to MAP: December 2001.

2 Purpose

To allow calculation of capillarity corrected equilibrium with thermodynamic calculation softwares such as MT-DATA.

3 Description

Two types of binary files are provided: *.dbs* and *.inx* files for direct use with MT-DATA. These data are replicated from the original databases, but a pressure dependency term has been added so that the MT-DATA user can increase the Gibbs energy of any of the precipitates by a given amounts.

The user should be aware that this pressure dependency terms are in no way real volumetric data. There only purpose is to allow the addition of 10^{-6} J mol^{-1} per Pascal. When using these database, a conventional calculation can be performed by setting the pressure to 1 Pa. If the Gibbs energy of, say, M23C6 is to be raised by 1000 J mol^{-1}, the pressure should be set to 10^9 Pa.

Once the file map_data_mtdata_capillarity uncompressed, the directory *databases* contains the following files:

README

Contains detailed instructions on how to install the databases and set up MT-DATA to use them.

cementite.dbs and cementite.inx

Binary files (database and index) providing thermodynamic data for cementite.

m23c6.dbs and m23c6.inx

Binary files (database and index) providing thermodynamic data for M23C6.

hcpa3.dbs and hcpa3.inx

Binary files (database and index) providing thermodynamic data for HCP_A3

sub_p.dbs and sub_p.inx

Binary files (database and index) providing thermodynamic data for the following substances: NTi, CTi, NNb, CNb, C0.479Nb, C0.877Nb, C0.98Nb.

SUBDIRECTORY loa_files

Contains the plain text load files corresponding to the above binary files.

Keywords

capillarity, coarsening, MT-DATA

APPENDIX FOUR

MAP_MT-DATA_KINETICS

This appendix presents the model described in chapter 6 and associated documentation following the MAP format, http://www.msm.cam.ac.uk/map/mapmain.html.

1 Provenance of Source Code

Thomas Sourmail and H. K. D. H. Bhadeshia
Phase Transformations and Complex Properties Group,
Department of Materials Science and Metallurgy,
University of Cambridge,
Cambridge, CB2 3QZ U.K.

This program is interfaced with MT-DATA,
National Physical Laboratory,
Teddington,
Middlesex,
TW11 0LW, U.K.

Added to MAP: December 2001.

2 Purpose

A program to estimate the kinetics of diffusion-controlled, multiple precipitation reactions in austenitic stainless steels. This program can also be used for the same purpose in different systems for which the SGTE databases provide thermodynamic data, but the user will be required to input the diffusion coefficients.

3 Specification

Language: FORTRAN
Product Form: Source Code
Operating System: tested on Solaris.

4 Description

MAP_MT-DATA_KINETICS contains the program which enable the user to obtain an estimate of the volume fraction of various precipitates forming in austenitic stainless steels during ageing at elevated temperature, as a function of time.
All thermodynamic calculations are handled internally by MT-DATA, therefore suppressing the need for the user to input driving forces or equilibrium compositions.
The software uses MT-DATA *.mpi* files, from which the user selects required phases. This file has to be created in first place, using the ACCESS module of MT-DATA.
Once uncompressed, MAP_MT-DATA_KINETICS contains:

kinetics.f

The source code for the program.

compile

A unix shell script to compile the program and link it to MT-DATA object files. It needs to be edited to point to the directory where the latter are found.

precipitate_data

A file containing information about a number of precipitates, that is, lattice parameter, number of atoms per unit cell, and parameters for nucleation (nucleation site density and interfacial energy).

spheregrowth.out and planargrowth.out

Contains 500 precalculated points for the solution to the sphere growth and planar growth equations as described in [1].

README

Complete instructions for installation and use.

5 References

1. Thomas Sourmail, *PhD thesis, Chapter 6*, available on http://www.msm.cam.ac.uk/phase-trans/

6 Input parameters

The user is only required to select the phases allowed in the calculation and the elements which are expected to control their growth, for example Cr and C in the case of $M_{23}C_6$. For most other input parameters, such as composition, ageing temperature and solution-treatment temperature, the user has the possibility to create, with the software files which can be used for faster access in later calculations.

7 Output parameters

The default output is
Time /s — Vf of precipitate 1 — Vf of precipitate 2 — etc
where Vf is the volume fraction.
This can be easily modified by editing the subroutine SNAPSHOT.

Keywords
Simultaneous precipitation reaction kinetics, austenitic stainless steels.

Bibliography

[1] Vanstone R. W. Advanced pulverised fuel power plant. In Strang A., Banks W. M., Conroy McColvin G. M., Neal J. C., and Simpson S., editors, *Advanced Materials for 21st Century Turbines and Power Plant*, pages 91–97. The Institute of Materials, 2000.

[2] Evans R. W. and Wilshire B. *Introduction to Creep.* The Institute of Materials, London, 1993.

[3] MT-DATA. National Physical Laboratory, Teddington, Middlesex, U.K., 1989.

[4] Lacombe P., Baroux B., and Beranger G., editors. *Stainless Steels.* Les Editions de Physiques, Les Ulis, 1993.

[5] Pickering F. B. Physical Metallurgical Development of Stainless Steels. In *Proc. Conf. Stainless Steels 84, Gothenburg, Sept 1984*, pages 2–28, 1984.

[6] Marshall P. *Austenitic Stainless Steels, Microstructure and Mechanical Properties.* Elsevier, London, 1984.

[7] Nippon Steel Corporation. Quality and Properties of NF709 Austenitic Stainless Steel for boiler tubing applications. Technical report, Nippon Steel Corporation, 1996.

[8] Davis J.R., editor. *Metals handbook*, volume 6. ASM International, Materials Park, OH, 10 edition, 1990.

[9] Naylor D. J. and Cook W. T. *Materials Science and Technology*, volume 7. VCH Publishers Inc., 1992.

[10] Gavrilnjuk V. G. and Berns H. *High Nitrogen Steels.* Springer-Verlag, Berlin, 1999.

[11] Masuyama F. New Developments in Steels for Power Generation Boilers. In Viswanathan R. and Nutting R., editors, *Advanced Heat Resistant Steels for Power Generation*, pages 33–47, London, 1998. The Institute of Materials.

[12] Kikuchi M., Sakabibara M., Otoguro Y., Mimura M., Takahashi T., and Fujita T. An Austenitic Heat Resisiting Steel Tube developed for Advanced Fossil Steam Plant. In *International Conference on Creep, Tokyo, April 14–18, 1986*, pages 215–220, 1986.

[13] Rios P. Expression for Solubility Product of Niobium Carbonitride in Austenite. *Mater. Sci. Techn.*, 4:324–327, 1988.

[14] Rios P. Method for Determination of Mole Fraction and Composition of a Multicomponent f.c.c. Carbonitride. *Mater. Sci. Eng.*, 142:87–94, 1991.

[15] Heilong Z. and Kirkaldy J. S. Thermodynamic Calculation and Experimental Verification of the Carbonitride-Austenite Equilibrium in Ti-Nb Microalloyed Steels. *Metal. Trans. A*, 23:651–657, 1992.

[16] Hughes H. Complex Nitride in Cr-Ni-Nb Steels. *J.I.S.I.*, pages 775–778, 1967.

[17] Andrén H. O., Henjered A., and Karlsson L. MX Precipitates in Stabilized Austenitic Stainless Steels. In *Proc. Conf. Stainless Steels 84, Gothenburg, Sept 1984*, pages 91–96, 1984.

[18] Andrén H. O., Henjered A., and Norden H. Composition of MC Precipitates in a Titanium Stabilised Stainless Steel. *J. Mater. Sci.*, 15:2365–2368, 1980.

[19] Wadsworth J., Woodhead J. H., and Keowm S. R. The Influence of Stoichiometry upon Carbide Precipitation. *Metal Sci.*, pages 342–348, 1976.

[20] Keown S. R. and Pickering F. B. Effect of Niobium Carbide on the Creep Rupture Properties of Austenitic Stainless Steels. In *Creep strength in steel and high-temperature alloys*, pages 229–234, London, 1974. The Metals Society.

[21] Adamson J. M. and Martin J. W. Tertiary Creep Processes in 20%Cr, 25%Ni Austenitic Stainless Steels of differing Nb/C Ratios. *J.I.S.I.*, pages 271–275, 1972.

[22] Jack D. H. and Jack K. H. Structure of Z-phase. *J.I.S.I.*, pages 790–792, 1972.

[23] Vodárek V. Morphology and Orientation Relationship of Z-phase in Austenite. *Scripta Metall. Mater.*, 25:549–552, 1991.

[24] Raghavan A., Klein C. F., and Marzinsky C. N. Instabilities in Stabilized Austenitic Stainless Steels. *Metall. Trans. A*, 23:2455–2467, 1992.

[25] Robinson P. W. and Jack D. H. Precipitation of Z-phase in a High-Nitrogen Stainless Steel. In Lula R., editor, *New Developments in Stainless Steel Technology*, pages 71–76, Metals Park, OH, 1985. Amer. Soc. Metals.

[26] Vorádek V. Effect of Niobium on the Microstructure and Creep Properties of AISI 316LN type steels. In Nordberg H. and Björklund J., editors, *Applications of Stainless Steels '92*, volume 1, pages 123–132. Jernkontoret and Avesta Research Foundation and ASM ineternational, 1992.

[27] Thorvaldsson T. and Dunlop G. L. Effect of Stabilizing Additions on Precipitation Reactions in Austenitic Stainless Steel. *Metal Sci.*, 16:184–190, 1982.

[28] Knowles G. The Creep Strength of a 20%Cr-25%Ni-Nb Steel Containing Controlled Particle Dispersions. *Metal Sci.*, pages 117–122, 1977.

[29] Uno H., Kimura A., and Misawa T. Effect of Nb on Intergranular Precipitation Behavior of Cr Carbides in N-bearing Austenitic Stainless Steels. *Corrosion*, 2(6):467–474, 1992.

[30] Beckitt F.R. and Clarck B.R. The Shape and Mechanism of Formation of $M_{23}C_6$ Carbide in Austenite. *Acta Metall.*, 15:113–129, 1967.

[31] Lewis M.H. and Hattersley B. Precipitation of $M_{23}C_6$ in Austenitic Steels. *Acta Metall.*, 13:1159–1168, 1965.

[32] Tanaka H., Murata M., Abe F., and Yagi K. The Effect of Carbide Distributions on long-term Creep Rupture Strength of SUS321H and SUS347H stainless steels. *Mater. Sci. Eng.*, A234:1049–1052, 1997.

[33] Singhal L.K. and Martin J.W. The Growth of $M_{23}C_6$ on Incoherent Twin Boundaries in Austenite. *Acta Metall.*, 15:1603–1610, 1967.

[34] Sasmal B. Formation of lamellar $M_{23}C_6$ on and near Twin Boundaries in Austenitic Stainless Steels. *Bul. Mat. Sci.*, 6:617–623, July 1984.

[35] Sasmal B. Mechanism of the Formation of $M_{23}C_6$ Plates around undissolved NbC Particles in a Stabilized Austenitic Stainless Steel. *J. Mater. Sci.*, 32:5439–5444, 1997.

[36] Ägren J. Computer Simulation of Diffusional Reactions in Complex Steels. *ISIJ International*, 32:291–296, 1992.

[37] Van der Ven A. and Delaey L. Models for the Precipitate Growth during the $\gamma \to \gamma + \alpha$ Transformation in Fe-C and Fe-Mn-C Alloys. *Progress in Mat. Sci.*, 40:181–264, 1996.

[38] Hättestrand and Andrén H.-O. Boron distribution in 9-12% chromium steels. *Mater. Sci. Eng.*, A270:33–37, 1999.

[39] Lai J. K. L. A Review of Precipitation Behaviour in AISI Type 316 Stainless Steel. *Mater. Sci. Eng.*, 61:101–109, 1983.

[40] Deighton M. Solubility of $M_{23}C_6$ in Type 316 Stainless Steel. *J.I.S.I.*, pages 1012–1014, 1970.

[41] Degalaix S. and Foct J. Nitrogen in Austenitic Stainless Steels(I). *Mém. Rev. Métall.*, pages 645–653, 1987.

[42] Biss V. A. and Sikka V. K. Metallography Study of Type 304 Stainless Steel Long-Term Creep-Rupture Specimen. *Metall. Trans. A*, pages 1360–1362, 1981.

[43] Thier H., Baumel A., and Schmidtmann P. Effect of Nitrogen on the Precipitation Behaviour of the Steel X 5 CrNiMo 17 13. *Arch. Eisenhuettenwesen*, 40:333–339, 1969.

[44] Minami Y., Kimura H., and Ihara Y. Microstructural Changes in Austenitic Stainless Steels during Long-Term Aging. *Mater. Sci. Techn.*, 2:795–806, 1986.

[45] Thorvaldsson T. and Dunlop G. L. Precipitation Reactions in Ti-stabilized Austenitic Stainless Steel. *Metal Sci.*, pages 513–518, 1981.

[46] Thorvaldsson T. and Dunlop G. L. The Influence of Composition on Precipitation in Stabilized Austenitic Stainless Steels. In *Proc. Int. Conf. on The strength of metals and alloys*, pages 755–760, 1979.

[47] Grot A. S. and Spruiell J. E. Microstructural Stability of Titanium-modified Type 316 and Type 317 Stainless Steel. *Metall. Trans. A*, pages 2023–2030, 1975.

[48] Bentley J. and Leitnaker J. M. Stable Phases in aged Type 321 Stainless Steel. In Collings E.W. and King H.W., editors, *The Metal Sience of Stainless Steels*, pages 70–91. The Metallurgical Society of AIME, 1978.

[49] Lai J. K. L. Precipitate Phases in Type 321 Steel. *Mater. Sci. Techn.*, 1:97–100, 1985.

[50] Stadelmaier H.H. Metal-rich metal-metalloid phases. In Plenum Press, editor, *Development in the Structural Chemistry of Alloy Phases*, pages 141–180, 1969.

[51] Weiss B. and Stickler R. Phase Instabilities During High Temperature Exposure of 316 Austenitic Stainless Steel. *Metall. Trans A*, 3:851–866, 1972.

[52] Brun G., Naour J.L., and Vouillon M. Etude de la Microstructure d'un Acier 316 au Titane apres Vieillissement et apres Irradiation aux Neutrons. *J. Nucl. Mater.*, 101:109–123, 1981.

[53] Williams T.M. Precipitation in Neutron-Irradiated Type 316 Austenitic STeel. In Institute of Metals, editor, *Stainless Steels 84*, pages 403–412, 1985.

[54] Titchmarsh J.M. and Williams T.M. Precipitates in Neutron-Irradiated Austenitic Stainless Steel . In Lorimer G.W, Jacobs M.H., and Doig P., editors, *Quantitative Microanalysis with High Spatial Resolution*, pages 223–228, London, 1981. Institute of Metals.

[55] R. F. A. Jargelius-Petterson. Precipitation in Nitrogen-Alloyed Stainless Steel at 850 °C. *Scripta Metall. Mater.*, 28:1399–1403, 1993.

[56] Lai J. K. L and Meshkat M. Kinetics of Precipitation of χ-phase and $M_{23}C_6$ Carbide in a Cast Type 316 Stainless Steel. *Metal Sci.*, pages 415–420, 1978.

[57] Barcik J. The Kinetics of σ-phase Precipitation in AISI 310 and AISI 316 Steels. *Metall Trans. A*, pages 635–641, 1983.

[58] Stoter L. P. Thermal Ageing Effects in AISI Type 316 Stainless Steel. *J.Mater.Sci.*, pages 1039–1051, 1981.

[59] R. F. A. Jargelius-Petterson. Precipitation Trends in Highly Alloyed Austenitic Stainless Steels. *Z. Metallkd.*, pages 177–183, 1998.

[60] Powell D. J, Pilkington R., and Miller D. A. The Precipitation Characteristics of 20%Cr/25%Ni-Nb Stanilised Stainless Steel. *Acta Metall.*, 36(3):713–724, 1988.

[61] Minami Y., Kimura H., and Tanimura M. Creep Rupture Properties of 18%Cr-8%Ni-Ti-Nb and Type 347H Austenitic Stainless Steels. In Lula R., editor, *New Developments in Stainless Steel Technology*, pages 231–242. Amer. Soc. Metals, 1985.

[62] Sumerling R. and Nutting J. Precipitation in a 20%Cr-25%Ni Steel Stabilized with Niobium. *J.I.S.I.*, pages 398–405, 1965.

[63] Ramaswamy V. and West D. R. F. NbC Precipitation in a 20%Cr-25%Ni-1%Nb Austenitic Steel. *J.I.S.I.*, pages 391–394, 1970.

[64] Williams T.M. and Titchmarsh J.M. Silicon rich Phases in Austenitic Alloys. *J. Nucl. Mater.*, 98:223–226, 1981.

[65] Powell D. J., Pilkington R., and Miller D. A. Influence of Thermal Ageing on Creep Properties of a 20/25/Nb-stabilised Steel. In *Proc. Conf. Stainless Steels 84, Gothenburg, Sept 1984*, pages 382–390, 1984.

[66] Ecob R. C., Lobb R. C., and Kohler V. L. The Formation of G-phase in 20/25 Nb Stainless Steel AGR Fuel Cladding Alloy and its Effect on Creep Properties. *J. Mater. Sci.*, 22:2867–2880, 1987.

[67] Barcik J. Mechanism of σ-phase Formation in Cr-Ni Austenitic Steels. *Mat. Sci. Techn.*, 4:5–15, 1988.

[68] Denham A.W. and Silcock J.M. Precipitation of Fe_2Nb in a 16-wt%Ni 16-wt%Cr Steel, and The Effect of Mn and Si Additions. *J.I.S.I.*, pages 585–592, 1969.

[69] Lai J. K. L. A Study of Precipitation in AISI Type 316 Stainless Steel. *Mater. Sci. Eng.*, 58:195–209, 1983.

[70] White W. E. and Le May I. Metallographic Observations on the Formation and Occurence of Ferrite, Sigma Phase, and Carbides in Austenitic Stainless Steels. Part II: Studies of AISI Type 316 Stainless Steel. *Metallography*, 3:51–60, 1970.

[71] Beattie H. J. and Hagel W. C. Intermetallic Compounds in Titanium-Hardened Alloys. *J. Metals*, pages 911–917, 1957.

[72] Dewey M. A. P., Sumner G., and Brammar I. S. Precipitation of Carbides in a Low-Carbon Austenitic Stainless Steel containing 20wt%Cr-25wt%Ni-0.7%Nb. *J.I.S.I.*, pages 938–944, 1965.

[73] Pickering F.B. Some Aspects of the Precipitation of Nickel-Aluminium-Titanium Intermetallic Compounds in Ferrous Materials. In Pickering F.B., editor, *The metallurgical evolution of Stainless Steels*, pages 391–401. The Metals Society, London, 1979.

[74] Satyanarayana D.V.V., Pandey M.C., and Taplin D.M.R. Creep Behaviour of a Precipitation Hardenable Austenitic Stainless Steel. *Trans. Indian Inst. Met.*, 49(4):419–423, 1996.

[75] Dulis E.J. Age-hardening Austenitic Stainless Steels. In Pickering F.B., editor, *The metallurgical evolution of Stainless Steels*, pages 420–441. The Metals Society, London, 1979.

[76] Tohyama A. and Minami Y. Development of the High Temperature Materials for Ultra Super Critical Boilers. In Viswanathan R. and Nutting J., editors, *Advanced Heat Resistant Steels for Power Generation*, pages 494–506. IOM Communications Ltd, IOM Communications Ltd, 1999.

[77] Rowcliffe A.F. and Nicholson R.B. Quenching Defects and Precipitation in a Phophorus-Containing Austenitic Stainless Steel. *Acta Metall.*, 20:143–155, 1972.

[78] Kolmogorov A. N. *Bulletin de l'Académie des Sciences de L'URSS*, 3:355–359, 1937.

[79] Johnson W. A. and Mehl R. F. *Transactions of the American Institute of Mining and Metallurgical Engineers*, 135:416–458, 1939.

[80] Avrami M. *Journal of Chemical Physics*, 7:1103–1112, 1939.

[81] Saunders N. and Miodownik A. P. *Calphad, Calculation of Phase Diagrams, A Comprehensive Guide*. Pergamond Press, Oxford, 1998.

[82] Hack K., editor. *The SGTE Casebook*. The Institute of Materials, London, 1996.

[83] National Physical Laboratory, Teddington, Middlesex, UK. *MT-DATA Handbook, Utility Module*.

[84] Christian J. W. *Theory of Transformation in Metals and Alloys*. Pergamond Press, Oxford, 1975.

[85] Johnson W. C., White C. L., Marth P. E., Ruf P. K., Tuominen S. M., Wade K .D., Russell K. C., and Aaronson H. I. Influence of Crystallography on Aspects of Solid-Solid Nucleation Theory. *Metall. Trans.*, 6:911–919, 1975.

[86] Bhadeshia H. K. D. H. *Bainite in Steels*. The Institute of Materials, London, 1992.

[87] Zener C. *Transactions of the American Institute of Mining and Metallurgical Engineers*, 175:15–51, 1946.

[88] Robson J. D. and Bhadeshia H. K. D. H. Modelling Precipitation Sequences in Power Plant Steels. Part 1 - Kinetic Theory. *Mater.Sci.Techn.*, pages 631–639, 1997.

[89] Coates D. E. Diffusion-Controlled Precipitate Growth in Ternary Systems I. *Metall. Trans.*, pages 1203–1212, 1972.

[90] Coates D. E. Diffusion-Controlled Precipitate Growth in Ternary Systems II. *Metall. Trans. A*, pages 1077–1086, 1973.

[91] Ziebold T. O. and Ogilvie R. E. Ternary Diffusion in Copper-Silver-Gold Alloys. *Trans. Met. Soc. AIME*, 239:942–953, 1967.

[92] Carolan R. A. and Faulkner R. G. Grain Boundary Precipitation of $M_{23}C_6$ in an Austenitic Steel. *Acta Metall.*, pages 257–266, 1988.

[93] Fujita N. and Bhadeshia H. K. D. H. Precipitation of Molybdenum Carbide in Steel: Multicomponent Diffusion and Multicomponent Capillarity Effects. . *Mater.Sci.Techn.*, 15, 1999.

[94] Jönsson B. Assessment of the Mobility of Carbon in fcc C-Cr-Fe-Ni Alloys. *Z. Metallkd.*, 85:502–509, 1994.

[95] Kirkaldy J.S. and Young D.J. *Diffusion in the Condensed State.* Institute of metals, London, 1987.

[96] Andersson J-O. and Ågren John. Models for Numerical Treatment of Multicomponent Diffusion in Simple Phases. *J. Appl. Phys.*, 72(4):1350–1355, 1992.

[97] Záhumenský P., Ševc P., and Janovec J. Kinetics of Growth of $M_{23}C_6$ Intergranular Precipitates in 18Cr-12Ni-2.5Mo Austenitic Stainless Steel. *Kovové Materiály*, 37:108–119, 1999.

[98] Assassa W. and Guiraldenq P. *Met. Corros. Ind.*, 621:170, 1977.

[99] Ågren J. Local Equilibrium and Prediction of Diffusional Transformations.

[100] Boeuf A., Coppola R., Zamboni F., Morlevat J. P., Rustichelli F., and Wenger D. Time Dependence at 600 °C and 650 °C of $M_{23}C_6$ Precipitate Composition in AISI 304 Stainless Steel. *J. Mater. Sci.*, 16:1975–1979, 1981.

[101] Hillerts M. *Phase Equilibria, Phase Diagrams and Phase Transformations, Their Thermodynamic Basis.* Cambridge University Press, Cambridge, 1998.

[102] Faulkner R. G. Discontinuous Precipitation Kinetics in Austenitic Steels. *Mater. Sci. Techn.*, pages 118–124, 1993.

[103] Morral J.E. and Purdy G.R. Particle Coarsening in Binary and Multicomponent Alloys. *Scripta Metall. Mater.*, 30(7):905–908, 1994.

[104] Thorvaldsson T., Rubinsztein-Dunlop H., Andrén H.-O., and Dunlop G.L. Analytical Electron Microscopy of Carbides Precipitates in a Stabilized Austenitic Stainless Steel. In *Quantitative Microanalysis with high spatial resolution*, pages 250–254. The Metals Society, 1981.

[105] Thorvaldsson T. and Dunlop G. L. Precipitation Reactions in Ti-stabilized Austenitic Stainless Steel. *Metal Sci.*, pages 513–518, 1981.

[106] G. F. Vander Voort, editor. *Applied Metallography.* Van Nostrand Reinhold Company, 1986.

[107] Suryanarayana C. and Norton M.G. *X-ray Diffraction, a Practical Approach.* Plenum Press, New York, 1998.

[108] Colombier L. and Hochmann J. *Stainless and Heat Resisting Steels.* Edward Arnold Ltd, 1965.

[109] Jenkins R. and Snyder R. L. *Introduction to X-ray Powder Diffraction.* Wiley-Interscience, New York, 1996.

[110] MacKay D. J. C. Probable networks and plausible predictions - a review of practical bayesian methods for supervised neural networks. *unpublished, can be obtained from http://wol.ra.phy.cam.ac.uk/mackay/BayesNets.html*, 1995.

[111] Mackay D. J. C. A Practical Bayesian Framework for Backpropagation Networks. *Neural Comput.*, 3:448–472, 1992.

[112] The British Steelmakers Creep Committee. BSCC high temperature data. Technical report, The Iron and Steel Institute, 1973.

[113] Jenkinson E. A., Day M. F., Smith A. I., and Hopkin L. M. T. The Long-Term Creep Properties of an 18%Cr-12%Ni-1%Nb Steel Steampipe and Superheater Tube. *J.I.S.I*, pages 1011–1024, 1962.

[114] Morris D. G. Creep Failure in Type 316 Austenitic Steel. *Metal Sci.*, pages 19–29, 1978.

[115] Strutt A. J. and Vecchio K. S. Simultaneous Oxidation and Sigma-phase Formation in a Stainless Steel. *Metal. Trans. A*, 30A:355–362, 1999.

[116] Keown S. R. and Pickering F. B. Effect of Niobium Carbide on the Creep Rupture Properties of Austenitic Stainless Steels. In *Creep strength in steel and high-temperature alloys*, pages 229–234. The Iron and Steel Institute, The Metal Society, 1974.

[117] Irvine K. J., Murray J. D., and Pickering F. B. The effect of Heat-Treatment and Microstructure on the High Temperature Ductility of 18%Cr-12%Ni-1%Nb Steels. *J.I.S.I.*, pages 166–179, 1960.

[118] Gittins A. The Kinetics of Cavity Growth in 20Cr/25Ni Stainless Seel. *J. Mater. Sci.*, 5:223–232, 1970.

[119] Takahashi T., Sakakibara M., Kikuchi M., Araki S., Ogawa T., and Nagao K. Develpment of a High-Strength 25Ni-20Cr Steel for Tubes in Ultra-Supercritical Power Boilers. In Armor A. F., Bartz J. A., Touchton G., and Valverde A. J., editors, *Improved Coal-Fired Power Plants*, volume 1, pages 3–17. Electric Power Research, 1991.

[120] Naoi H., Ohgami M., Araki S., Ogawa T., Fujita T., Mimura H., Sakakibara H., Sogon Y., and Sakurai H. Development of Tubes and Pipes for Ultra-Supercritical Thermal power Plant Boilers. Technical Report 57, Nippon Steel, april 1993.

[121] Araki S., Takahashi T., Sakakibara M., Mimura H., Ishitsuka T., Naoi H., and Fujita T. Behaviors of Microstructures and Precipitates during Creep and Aging of High-Strength 20Cr-25Ni Steel for Tubes in Ultra-Supercritical Power Boilers. In Liaw P. K., Viswanathan R., Murty K. L., Simonen E. P., and Frear D., editors, *Microstructures and Mechanical Properties of Aging Materials*, pages 99–105. TMS, November 1992.

[122] Araki S., Takahashi T., and Sakakibara M. Life Prediction Technique for Stainless Steels in Hot Corrosion Environment of Boilers. In *Life Prediction of Corrodible Structures*, pages 1–15, Hawai, 1991. NACE.

[123] Takahashi T., Kikuchi M., Sakurai H., Nagao K., Sakakibara M., Ogawa M., Araki T., and Yasuda H. Development of High-Strength 20Cr-25Ni (NF709) Steel for USC Boiler Tubes. Technical Report 38, Nippon Steel, july 1988.

[124] Mathew M. D., Sasikala G., Rao K. B. S., and Mannan S. L. Creep Deformation and Fracture Behavior of a Type 316LN Stainless Steel. In Woodford D. A., Townley C. H. A., and Ohnami M., editors, *Fifth International Conference on Creep of Materials*, pages 577–585, Florida, May 1992.

[125] Elliott D. and Tupholme S. M. An Introduction to Steel Selection: Part 2, Stainless Steels. Oxford University Press, 1981.

[126] F. B. Pickering. *Physical Metallurgy and the Design of Steels.* Applied Science Publishers Ltd, London, 1978.

[127] Sourmail T. Precipitation in Creep Resistant Austenitic Stainless Steels. *Mat. Sci. Tech.*, 17:1, 2001.