Title: Martensitic transformations and shape memory alloys. Welding and thermomechanical processing of steels.

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Martensitic transformations and shape memory alloys. Welding and thermomechanical processing of steels.

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HIGHER DOCTORAL DEGREE THESIS

Doctor of Science

from

THE UNIVERSITY OF WOLLONGONG

by

Druce Patrick Dunne

Materials Engineering

May 2003

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PARTS 1 – 3 and APPENDICES

PART 1. CONFORMANCE WITH HIGHER DOCTORAL DEGREE REQUIREMENTS

1.1 Basis of the Application

I am a graduate of the University of New South Wales (UNSW), with a 1st Class Honours B.Sc (Met.) degree with University Medal (1964) and a PhD (1968). Although I graduated from the Kensington (Sydney) Campus rather than Wollongong University College, I have held a continuing academic position at the University of Wollongong since 1970, initially as a staff member of the Wollongong University College of UNSW and then as an academic of the University of Wollongong when it became autonomous in 1975. I am therefore applying for a Doctor of Science degree by publication under Rule 803 1(b) (University of Wollongong Postgraduate Calendar, Part 8, Higher Doctoral Degree Rules), as a full-time academic staff member "with standing of not less than eight years after admission to a first degree at another university".

1.2 Required Information

In relation to requirement 803 2(a), the academic unit associated with my scholastic activities is Materials Engineering, formerly the Department of Metallurgy and then the Department of Metallurgy and Materials Engineering. The unit name was subsequently changed to the Department of Materials Engineering (1987) then the Discipline of Materials Engineering (1998).

The list of publications required of 803 2(b) is given in Part 2 together with the estimated percentage contributions of the authors. In relation to 803 2(d)(v), none of these listed publications "have (previously) been submitted for any qualification of any (other) tertiary institution". Copies of these publications are presented in Part 4, as required by 803 2(c). An overview that demonstrates that "the collective works provide an original and significant contribution to knowledge" (803 2(d)) is given in Part 3, which treats publications emanating from two separate streams of work (in Sections 3.2 and 3.3). Similarly, "evidence that the publications have standing as significant and sustained contributions to knowledge" (803 2(d) (iv)) is presented throughout Sections 3.2 and 3.3 and in the form of a summaries in Subsections 3.2.1 and 3.3.1.

My curriculum vitae is given in Appendix 1 and the complete list of my publications at the time of submission is provided in Appendix 2.

PART 2. LIST OF PUBLICATIONS FORMING THE BASIS OF THE APPLICATION

2.1 Martensitic Transformations and Shape Memory Alloys

1. D.P. Dunne and J.S. Bowles, "Measurement of the Shape Strain for the (225) and (259) Martensitic Transformations", Acta Metallurgica, 1969, **17**, p. 201. **60/40***

2. J.S. Bowles and D.P. Dunne, "The Role of Plastic Accommodation in the (225) Martensite Transformation", Acta Metallurgica, 1969, **17**, p. 677. **60/40**

3. D.P. Dunne and C.M. Wayman, "On the Validity of Methods for Determining the Shape Strain in Deformation Twinning and Martensitic Transformations", Acta Metallurgica, 1970, **18**, p. 981. **80/20**

4. D.P. Dunne and C.M. Wayman, "The Crystallography of Ferrous Martensites', Metallurgical Transactions, 1971, 2, 2327. Also printed in "Formation of Martensite in Iron Alloys", Metallurgical Society of AIME Symposium Proceedings, ed. by K. Kinsman amd C. Magee, May, 1970. **50/50**

5. D.P. Dunne and C.M. Wayman, "An Assessment of the Double Shear Theory as Applied to Ferrous Martensitic Transformations", Acta Metallurgica, 1971, **19**, p. 425. **75/25**

6. D.P. Dunne and C.M. Wayman, "The Effect of Austenite Ordering on the Martensite Transformation in Fe-Pt Alloys Near the Composition Fe_3Pt: I. Morphology and Transformation Characteristics", Metallurgical Transactions.,1973, **4**, p.137. **80/20**

7. D.P. Dunne and C.M. Wayman, "The Effect of Austenite Ordering on the Martensite Transformation in Fe-Pt Alloys near the Composition Fe_3Pt: II. Crystallography and General Features", Metallurgical Transactions, 1973, **4**, p.147. **80/20**

8. J.S. Bowles and D.P. Dunne, "The Crystallographic Theory of Martensite Transformations", Metal Science Journal, 1973, **1**, p.118. *(invited)* **60/40**

9. D.P. Dunne, "Transformation-Induced Anelasticity", Journal of the Australian Institute of Metals, 1974, **19**, p. 28. **100**

10. D.P. Dunne, "A Model for the Interface of $(3, 15, 10)_F$ Martensite in Steel", Scripta Metallurgica, 1977, **11**, p. 1017. **100**

11. D.P. Dunne, "The Interface Structure of Martensite in Fe_3Pt", Scripta Metallurgica, 1978, **12**, p. 143. **100**

12. D.P. Dunne and N.F. Kennon, "Ageing of Copper-based Shape Memory Alloys", Metals Forum, 1981, **4** (3), pp. 176-183. **50/50**

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* estimated percentage contributions of authors in stated order

13. N.F. Kennon and D.P. Dunne, "Shape Strains Associated with Thermally-induced and Stress-induced Martensite in a Cu-Al-Ni Shape Memory Alloy", Acta Metallurgica, 1982, **30**, pp. 429-435. **50/50**

14. N.F. Kennon, D.P. Dunne and L.A. Middleton, "Ageing Effects in Copper-based Shape Memory Alloys", Metallurgical Transactions, 1982, **13A**, p. 551. **40/40/20**

15. M.Ferry, N. Kennon and D. Dunne, "Shape Strains Associated with Forward and Reverse Martensitic Transformation in a Cu-Al-Ni Shape Memory Alloy", Mater. Sci. Forum, 1990, **56-58**, pp. 435-440. **40/40/20**

16. D.Dunne, J. Van Humbeeck and M. Chandrasekaran, "Effect of Quenching Rate on the Structure and Transformation Characteristics of a Cu-Al-Ni-Ti-Mn Shape Memory Alloy", Mater. Sci. Forum, 1990, **56-58**, pp. 463-468. **60/30/10**

17. D. Dunne and H. Li, "The Effect of Parent Phase Strengthening on Shape Memory Behaviour in Ferrous Alloys", Proceedings of ICAM '93, <u>18B</u>, Tokyo, Japan, 1993, pp. .955-960. *(invited)* **70/30**

18. D. Dunne and H. Li, "The Mechanism of Thermomechanical Training of Fe-Mn-Si-Cr-Cu Shape Memory Alloys", ICOMAT '95, ed. R Gotthardt and J. Van Humbeeck, Journal de Physique IV, 1995, pp. 415-420. **50/50**

19. N. Kennon, D. Dunne and J.H. Zhu, "Effect of Precipitation on Martensitic Transformation and Shape Memory Behaviour in Rapidly Solidified Ni-Al Alloys", ICOMAT '95, ed. R Gotthardt and J. Van Humbeeck, J. de Physique IV, 1995, p. 1041. **20/40/40**

20. L. Chen, D. Dunne and N. Kennon, "Determination of the Parent Grain Orientation and Habit Plane Normals of Martensite in a Cu-Al-Ni-Mn Shape Memory Alloy", J. Materials Sci., **32**, 1997, pp. 3769-3773. **30/50/20**

21. D. Dunne, "Martensitic Iron-Platinum Alloys", International Conference on Displacive Transformations, University of Illinois, USA, 1998, TMS Pub., Ed by K. Inoue et al., pp. 133-140. *(invited)* **100**

22. D.P. Dunne and J.H. Zhu, "The Role of Vacancies on Inhibition of Reverse Transformation in Rapidly Solidified Ni66Al34 Alloy," Proc. ICOMAT'98, S.C. Bariloche, Argentina, Materials Science and Engineering A273-275, 1999, pp. 690-696. **70/30**

23. D.P. Dunne, "Interfacial Structure and the Shape Memory Effect", Proc. Int. Symp. on Shape Memory Materials, SMM'99, May 1999, Kanazawa, Japan, pub. in Materials Science Forum, Vols 327-328, ed. T. Saburi, 2000, pp. 315-322. **100**

24. D. Dunne, "Functional Memory Metals", Materials Forum, **24**, 2000, pp. 95-108. *(invited).* **100**

25. D. Dunne and D.Z. Liu, "Crystallography and Interfacial Structure of Twinned Shape Memory Martensite", Proc. ICOMAT'02, Helsinki, Finland, 2002, accepted for publication in J. de Physique, June 2003. **60/40**

2.2 Welding and Thermomechanical Processing of Steels

1. D.P. Dunne and R.L. Dunlea, "Grain Shape Anisotropy in Cold Rolled and Recrystallised Al-killed Steel", Metals Forum, 1978, **1**, p. 156. **60/40**

2. R. Smith, T. Chandra and D.P. Dunne, "Isothermal Ferrite Formation from Deformed Austenite in a V-bearing HSLA Steel", Proceedings of 2nd Riso Intemational Symposium on Metallurgy and Materials Science, Roskilde, Denmark, Sept. 1981, p. 371. **40/20/40**

3. D.P. Dunne, "Recrystallization in a Cold-rolled Fe-V-C Alloy containing Fine Carbides", Metal Science, 1982, **16**, p. 259. **100**

4. D.P. Dunne, R.W. Smith and T. Chandra, "The Effect of Temperature and Deformation on Isothermal Structural Changes in Austenite in a Vanadium Bearing HSLA Steel", Proc. Int. Conference on HSLA Steels, Wollongong, Australia, 1984, p. 188. **40/40/20**

5. R.M. Smith, J. Williams and D.P. Dunne, "Ageing of Hot-rolled HSLA Steels", Metals Forum, 1982, **13**, p. 281. **40/10/50**

6. D.P. Dunne, T. Chandra and S. Misra, "Recrystallization of Austenite in a Hot Rolled Titanium HSLA Steel with Ti:N>3.4", Microalloying '85, Proceedings of a Conference on HSLA Steels, Beijing, China, Nov. 1985, p. 207. **50/10/40**

7. D.P. Dunne, R. M. Smith and T. Chandra, "Ferrite Size Distributions in Hot Rolled HSLA", Microalloying '85, Proceedings of a Conference on HSLA Steels, Beijing, China, Nov. 1985, p. l41. **50/40/10**

8. A.L. Wingrove, D.P. Dunne and N.F. Kennon, "The Tekken Test - The Influence of Welding Parameters", Australian Welding Research Journal, 1985, Dec., p.8. **60/30/10**

9. R.M. Smith, D.P. Dunne and T. Chandra, "Precipitation Hardening of Ferrite in HSLA", Proceedings of 'Thermec 88', Tokyo, 1988, p. 275. **40/50/10**

10. R. M. Smith and D.P.Dunne, "Structural Aspects of Alloy Carbonitride Precipitation in Microalloyed Steels", Materials Forum, Special Bicentennial Edition, 1988, **11**, p. 166; also published in 'Engineering Materials 200', ed. by J. Watson, Transtech Publications, Switzerland,1988. *(invited)* **50/50**

11. B. Feng, T. Chandra and D. Dunne, "The Effect of Alloy Nitride Particle Size Distribution on Austenite Grain Coarsening in Ti and Ti-Nb Bearing HSLA Steels", Materials Forum, 1989, **13**, p. 139-146. **40/20/40**

12. D. Dunne, B. Feng and T. Chandra, "The Effect of Ti and Ti-Nb Additions on Ferrite Formation and Restoration during Intercritical Rolling and Holding of C-Mn Structural Steels", ISIJ International, **31**, 1991, p. 1354-1361. **40/40/20**

13. A. Abdollah-Zadeh and D. Dunne, "Effect of Niobium on Static Recrystallization of Hot Deformed Austenitic HSLA Steel Analogue Alloy", HSLA 95 Conference, Beijing, Oct. 1995, p. 157-162. **50/50**

14. D. Dunne, "Weldable Copper Strengthened Low Carbon Steels", Proceedings of HSLA Steels '95 Conference, Beijing, Oct. 1995, pp. 90-98. *(invited)* **100**

15. B.S. Ghasemi, D. Yu and D.Dunne, "Age Hardening in a Cu-bearing High Strength Low Alloy Steel", ISI Japan International, 1996, **36**, pp. 61-67. **40/10/50**

16. D.Dunne, B.S. Ghasemi and D. Yu, "Isothermal Transformation Products in a Cu-bearing HSLA Steel", ISIJ International, 1996**,** **36**, pp. 324-333. **50/40/10**

17. P.Manohar, D. Dunne, T. Chandra and C. Killmore, "On Grain Growth Predictions in Microalloyed Steels", ISIJ Inernational, 1996, **36**, p. 194. **50/20/20/10**

18. A. Abdollah-Zadeh and D. Dunne, 'The Effect of Niobium on the Recovery Deformed Austenite', Proc. of Int. Symp. on Recovery and Recrystallisation in Steel, Hamilton, Canada, 1995 37th MWSP Conf. Proc. ISS XXXIII, 1996, pp. 689-694. **50/50**

19. N. Alam, H. Li, L. Chen and D. Dunne, "Fracture Morphology of Hydrogen-assisted Cold Cracking in Steel Weldments", Aust. Welding Journal, Welding Res. Suppl., Vol 32, 1, 1997, pp. 43-47. **40/10/10/40**

20. M. Frewin, D. Dunne and A. Scott, "Structural Evolution of Pulsed Nd:YAG Laser Welds of AISI 1006 Steel", Science and Technology of Welding and Joining, Vol.3, No. 3, 1998, pp. 145-150. **50/40/10**

21. X. Lin and D. Dunne, "Microstructural and Hardness Gradients Across the HAZ of Submerged Arc Welded Copper Bearing Structural Plate Steel", Aust. Weld. J. Res. Suppl., **43**, no.4, 1998, pp. 38-47. **40/60**

22. F.J. Barbaro, I.D. Henderson, D.P. Dunne, M.J. Painter, J. Norrish and R.P. Harrison, "Quality and Productivity Improvements in the Field Welding of High Strength Thin Walled Pipelines," Proc. of WTIA 46th Annual Conference: Planning, Production and Productivity, Perth, Nov. 1998, Publication 5. **50/10/10/10/10/10**

23. D.P. Dunne, "Ferrite Morphology and Residual Phases in Continuously Cooled Low carbon Steels," Materials Forum, **23**, 1999, pp. 63-76. *(invited)* **100**

24. N. Alam, D. Dunne and F. Barbaro, "Weld Metal Crack Testing for High Strength Cellulosic Electrodes," 1st Int. Conf. on Weldmetal Hydrogen Cracking in Pipeline Girth Welds, Wollongong, March 1999, WTIA-CRC MWJ. *(invited).* **50/40/10**

25. Yan Wang Chen, D. Dunne, J. Norrish and J. Szalla, "Microstructure and Mechanical Properties of GMA Welded Zincalume G550 Sheet Steel", Aust Welding Journal, Welding Res. Suppl., **45**, 4th Quarter, 2000, pp. 39-47. **40/30/20/10**

3. CASE FOR AWARD OF DSc DEGREE BY PUBLICATION

3.1 Introductory Statement

My research work has been based on both fundamental and applied science, with a dominant theme of steel metallurgy. During an academic career spanning more than thirty years, the emphasis of my research has shifted progressively towards the applied end of the research spectrum.

The selected list of refereed, published papers that form the basis of this DSc thesis not only reflects the dual fundamental and applied nature of my research work, but also the sustained pursuit of significant scientific and technological objectives. The publications are divided into two streams: martensitic transformations and shape memory alloys (Section 2.1); and welding and thermomechanical processing of steels (Section 2.2). The first stream has involved research that tends to be more fundamental in nature, whereas the second stream has more immediate industrial significance. Although these fields represent the two major thrusts of my research work, the complete list of publications (Appendix 2) indicates wider activity that includes the fields of surface engineering, creep of pressure vessel steels, engineering ceramics, recrystallisation in non-ferrous materials, solidification and archeometallurgy.

Each paper presented involved significant personal input – intellectually and/or experimentally; and, invariably, in the writing of the manuscript. In general, I strive for quality in publications that bear my name and I make it a practice not to accept offers of token authorship. The approximate percentage contribution by me to each paper reproduced in this volume is given in the list of publications given in Part 2. Although research activity in a university environment is primarily collaborative, as it normally involves the supervision and training of research students, it is noteworthy that eight of the fifty listed publications are sole author contributions. These sole author papers reflect novel ideas and concepts, reviews of fields of expertise, or summaries of significant bodies of work carried out by postgraduates and/or postdoctoral researchers under my intellectual guidance over periods of years.

My case for award of a Doctor of Science degree based on published work separately considers the two major streams of my research work in Sections 3.2 and 3.3.

3.2 Martensitic Transformations and Shape Memory Alloys

The first two papers that I wrote on martensitic transformations were the product of my PhD research program at the University of New South Wales under the supervision of Professor John Bowles. Publication 2, "The Role of Plastic Accommodation in the $\{225\}_F$ Martensite Transformation", addresses the classical and seemingly intractable problem of theoretically predicting the observed crystallography of $\{225\}_F$ martensite in plain carbon and some alloy steels. The phenomenological crystallographic theory, presented by Bowles and Mackenzie in the early 1950s (the BM theory) [1,2], is capable of predicting the experimentally measured crystallographic features of the $\{3\ 10\ 15\}_F$ transformation in high carbon, high nickel steels and for a wide range of non-ferrous alloys. However, in order to account for the $\{225\}_F$ transformation, a uniform 1.5% dilatation of the otherwise invariant habit plane had to be invoked. This hypothesis was highly controversial and, consequently, Bowles and Morton [3] attempted to confirm experimentally the existence of an interfacial dilatation. Although their measurements of the shape strain provided evidence that a dilatation did occur, subsequent research that I conducted on similar steels did not support the presence of the dilatation (Publication 1). This experimental work was significant as it was the forerunner of other published findings [4-6] that led to the universal abandonment of the concept of an interfacial dilatation. A modified version of the phenomenological crystallographic theory, the plastic accommodation model, was conceived by Bowles, and developed by us collaboratively into the form presented in Publication 2. This model was a specific case model that was a precursor to subsequent general double shear theories [7, 8]. However, the plastic accommodation model for the $\{225\}_F$ transformation gives predictions that are, arguably, closer to experimentally measured values than any theoretical models that have since been advanced.

One of the most prominent geometric features of martensitic transformation is the surface relief produced by transformation. This relief is a manifestation of a homogeneous shape strain in the transformed volume. Publication 3 is the benchmark paper on methods for measurement of this homogeneous shape strain (the invariant plane strain). Appropriate combinations of line and plane displacements, caused by the transformation, were used to provide the theoretical framework of the methods for shape strain determination. Measured displacements, combined with experimentally determined habit plane traces and parent grain orientations, were used to quantify the elements of the shape strain: the invariant (habit) plane, the strain direction and the magnitude of displacement. The accuracy of the methods was assessed using measurements on deformation twins in pure tin, for which the twinning elements are precisely known. This work confirmed that the methods developed are capable of measuring the martensitic shape strain with both high precision and high accuracy.

This publication and the following four were based on research that I undertook as a postdoctoral researcher at the University of Illinois, working in collaboration with Professor Marvin Wayman. Publication 4 is an expert status report on the level of understanding of the crystallography of ferrous martensite at the time of writing; and Publication 5 contributes a detailed analysis and testing of the double shear theory that was developed independently by Acton and Bevis [7] and Ross and Crocker [8]. The shortcomings of this theory in accounting for the crystallography of ferrous martensites were clearly demonstrated.

Publications 6 and 7, on "The Effect of Austenite Ordering on the Martensite Transformation in Fe-Pt Alloys near the Composition Fe_3Pt", reported the first discovery of thermoelastic martensitic transformation in Fe-based alloys. This result is important as thermoelastic transformation is a sufficient condition for shape memory (SM) behaviour and it opened up the attractive prospect of developing a 'shape memory steel'. Moreover, the research demonstrated unambiguously that long range ordering of the parent austenite phase is highly significant in establishing thermoelastically reversible phase transformation. The wider ramifications of these results were taken up in the review of shape memory phenomena in Publication 9. My analysis of shape memory effects in this paper was one of the first to conclude that reversible interface motion, rather than thermoelastic transformation, is the key to shape memory. This hypothesis was based on observations of reversible martensitic transformation in partially ordered Fe-Pt alloys that occurred with a relatively large temperature hysteresis (50 – 200˚C, depending on degree of order). Such transformation is referred to as semi-thermoelastic. The transformation hysteresis decreases sharply with increasing order (to less than about 20 ˚C), thermoelastic reversibility develops, and shape memory behaviour is exhibited. Nevertheless, partially ordered alloys still exhibit one-way shape memory [9]. More than a decade later, Fe-Mn-Si alloys were developed that also exhibit a wide transformation hysteresis (200˚C), rather than thermoelasic transformation, but they also show a significant one-way shape memory effect [10].

Another invited status report on the crystallographic theory of martensitic transformations, co-written with Bowles, was published in 1973 (Publication 8). This was a succinct analysis of the status of the crystallographic theory and unresolved problems at the time of writing.

Publication 10 ("A Model for the Interface of {3,15,10} Martensite in Steel") addresses the nature of the interface of twinned martensite and provides a theoretical model for predicting the crystallography of the terminating twin interfaces in twinned martensite plates. This model is based on the assumption that the facet planes are essentially unrotated planes of the homogeneous lattice strain that describes the fine-scale transformation from the parent to the martensite structure. Unrotated planes would be expected to minimise the fine-scale interfacial strains associated with atomic mismatch across the interface. Although I applied this concept originally to $\{3,10,15\}_F$ martensite in steel, the model has been shown recently to be applicable to twinned martensites in non-ferrous alloys [11]. I am currently investigating the generality of the twin facet model by testing its applicability to twinned Cu-based martensites [12-14].

Publication 11 on the interface structure of Fe_3Pt alloys introduced the concept of the different levels of strain accommodation that accompany the formation of martensite plates. The 'primary' accommodation effect on which the crystallographic theories are based is the operation of a lattice invariant shear in the form of slip, twinning or faulting to establish an interface between parent and martensite that is macroscopically undistorted (invariant). The term 'secondary' accommodation was used to describe the structural response to finer scale elastic strains at the interface arising from imperfect atomic matching across the interface.

The twin facet model addresses this fine scale accommodation effect for twinned martensite. The final type of accommodation ('tertiary') is related to the transformational shear and volumetric strains. The shear strains can be effectively cancelled by the formation of self-accommodating groups of plates of different crystallographic variants. However, the volume change cannot be accommodated other than by elastic and/or plastic (irreversible) strains in the parent or martensite or in both phases. Hence, thermoelastically reversible transformations are characterised by volume changes small enough to be elastically accommodated.

From 1980, I started a long and fruitful collaboration with Dr Noel Kennon at the University of Wollongong, initially concentrating on studies of non-ferrous shape memory alloys. We realised that a basic practical limitation of shape memory alloys used in two-way memory applications, such as thermal switches and actuators, resides in the metastable nature of the martensitic phase transformation. Thermal cycling to effect a shape change will eventually lead to decomposition to more thermodynamically stable phases, with the loss of reversible martensitic transformation and shape memory. Therefore, we embarked on investigations of the kinetics of ageing in copper-based shape memory alloys (Publications 12 and 14). Publication 12 was presented in a special shape memory alloy edition of Metals Forum in 1981, which Kennon and I were invited to produce and edit. We solicited papers from leading international researchers in this field: Delaey and Van Humbeeck (Belgium), Banks, Perkins and Wayman (USA), Otsuka (Japan) and the resulting edition provided up-to-date research findings and reviews of the status of research in SM alloys. Our kinetic studies of Cu-based alloys contributed quantitative data on the ageing kinetics (stability) of Cu-Ni-Al and Cu-Zn alloys and confirmed the significantly higher metastability of the Cu-Zn alloy system.

We also recognised that rationalising the crystallography of shape memory martensites in terms of the theory was an important step in understanding the mechanism of the SM effect. Other challenges that we undertook were to establish experimentally that the crystallographies of thermally and stress-induced martensites were the same in the same alloy; and to prove that the crystallographies of the forward and reverse transformations were the inverse of one another. The former problem was resolved through the research reported in Publication 13 for $_{1}'$ martensite in Cu-Al-Ni alloy. The crystallographic measurements were found to be indistinguishable for the two types of martensite. However, the measured shape strain and orientation relationship could not be accounted for by the BM theory using the commonly assumed lattice invariant shear of Type I twinning on the {112} plane of the orthorhombic martensite structure. The problem was subsequently resolved by Otsuka and co-workers who demonstrated that Type II twinning occurs [15]. The other challenge, to establish that the crystallographies of the forward and reverse transformations of SM alloys are equivalent, was achieved through the experimental results reported in Publication 15. This issue is not trivial, since residual surface rumpling has been reported following reverse martensitic transformation of martensite plates formed at initially smooth surfaces [16], implying that complete recovery of the shape change is not achieved.

A period of study leave at the Katholique Universiteit, Leuven in Belgium in 1987 stimulated new, more applied, directions of research that included studies of a grain refined commercial copper-based alloy (CANTIM - a Cu-Al-Ni-Ti-Mn alloy); development of improved Fe-Mn-Si-based SM alloys; and investigations of SM alloys produced by melt spinning. Publication 16 reports the effect of quenching rate on the structure and transformation characteristics of CANTIM and marks a developing interest in the rate of the first quench to form martensite and its influence on transient stabilisation effects associated with the first reverse transformation cycle.

Research on the effect of substitutional and interstitial alloying elements on the reversibility of stress-induced martensite in Fe-Mn-Si-based alloys, together with experience of the effect of ordering on reversibility of ' martensite in Fe-Pt, formed the basis for an invited review titled the "Effect of Parent Phase Strengthening on Shape Memory Behaviour in Ferrous Alloys" (Publication 17). This paper is significant insofar as it was one of the first analyses to recognise the general importance of the strength (slip resistance) of the austenite on transformation reversibility and shape memory. It also presented early results on the concept of strengthening of the austenite of Fe-Mn-Si-based alloys using coherent Ni_3Al precipitates. Although our data indicated an adverse effect due to strong pinning of Shockley partial (transformation) dislocations, subsequent work by other researchers [17] using smaller volume fractions of NbC precipitates showed the favourable effect on shape recovery strain that I had expected.

The research project on the development of improved Fe-Mn-Si-based SM alloys led to an alloy containing Cr and Cu that, on 'training', displays one of the highest shape recoveries (5.4% strain) so far reported in the literature (Publication 18). An investigation of the corrosion resistance of this new alloy (Reference 43 in Appendix 2) also showed that it is at least as high as the previously developed Fe-Mn-Si-Cr-Ni "stainless steel" alloys [18]. Trials were conducted using the Cr-Cu-bearing alloy to produce heat shrinkable couplings for high pressure (< 80 MPa), small diameter (< 25 mm) tubing for gas-lines in a project with an industrial partner. Although pressure tests showed that typical service pressures could be sustained, the required safety factor precluded the use of currently available iron-based heat shrinkable couplings, without incorporating additional mechanical interlocking. This latter requirement reduces the cost-effectiveness in comparison with welding or brazing. However, the effectiveness of Fe-Mn-Si-based shape memory couplings for larger diameter, lower pressure pipelines has been reported [19].

My interest in the effect of quenching rate on martensitic transformation was pursued by means of alloy preparation by melt spinning (rapid solidification) using a stainless steel wheel. This alloy production technique results in strip about 40 m thick, at cooling rates approaching 10^6 °C/s. A major focus was alloys near the composition Ni_2Al (Publications 19 and 22). Melt spinning was found to suppress precipitation of Ni_5Al_3, but subsequent DSC monitoring of the transformation by heating at a low rate causes copious fine precipitation in the martensite and destruction of the capacity of the alloy for martensitic transformation on further cycling (Publication 19). It was discovered that rapid upquenching into the state, with precipitation in the phase, allowed normal reversible martensitic transformation. Subsequent analysis of the DSC data in Publication 22 demonstrated that the observed effects are consistent with the presence of a substantial excess of vacancies in the rapidly solidified ribbon that decays during slow heating with enhanced precipitation of Ni_5Al_3.

Publication 20 was based on a novel method that I developed for the determination of the parent grain orientation in fully transformed $_1$ phase Cu alloys by measuring the corresponding traces of junction planes of four plate self-accommodating clusters in two surfaces at right angles. The junction planes are precisely {110} planes of the grain and locating two or more normals of these planes enables the determination of the grain orientation and subsequently, the crystallography of the habit plane. The measured average habit plane normals in four different grains were about 1.6° from $(155)_1$ and showed a scatter of less than ± 1.2°.

The retirement of Professor Marvin Wayman from the University of Illinois in 1998 was marked by a major symposium on 'Displacive Phase Transformations and Their Applications in Materials Engineering'. I was invited to present a review of martensitic transformation in Fe-Pt alloys (Publication 21) and in integrating and rationalising my own and other data, I arrived at two novel hypotheses concerning the effect of austenite order on thermoelastic martensite transformation in this alloy. The first is that limited experimental data presented in Publication 7 is consistent with the predictions of the BM theory that ordering shifts the habit plane by about 6° from near $(3\ 15\ 10)_F$ towards the $(011)_F$ plane, establishing nearly two-fold symmetry and allowing the martensite to form as four plate self-accommodating clusters. The enhancement of thermoelasticity by parent phase ordering was rationalised in terms of strain limiting factors (low volume change, low shear component of the shape strain, low chemical driving force) and strain accommodating factors (high elastic limit of austenite, formation of self-accommodating plate groups, fine transformation twins). The first set of factors reduces the magnitudes of the strains that need to be accommodated and the second set improves the strain cancelling efficacy of the primary accommodation (twinning), and enhances the capacity of the alloy to effect any secondary and tertiary accommodation by elastic strain.

The second novel concept that I raised and discussed in Publication 21 is that of a continuous spectrum of martensite crystallographies as plates form or grow progressively with falling temperature in the M_s–M_f range. This condition arises because the lattice parameter of the austenite in FePt shows a strong dependence on temperature, whereas the martensite parameters are relatively insensitive to temperature [20]. Although this effect may be unusually strong in Fe-Pt, it is likely to be a general effect in transformations that are characterised by an extended M_s–M_f range.

Publications 23 and 25 are concerned with ongoing analysis of the applicability of the twin facet model to twinned $_1'$ martensite in Cu-Al-Ni alloys. Greater than expected complexity and flexibility of the interface structure has been discovered, with the presence of both well-defined facet planes associated with the twin termini in the interface; and regular side-plates emanating from the smaller of the two twin volumes. This second effect is associated with the crystallographic 'degeneracy' of the transformation, as the Type II twin plane is nearly a habit plane variant, allowing 'extension' into the parent phase, presumably as a type of alternative secondary accommodation response to fine-scale interfacial strain.

3.2.1 Standing and significance of research

My international stature in the field of martensitic transformations is reflected by four invited/keynote lectures at international conferences, an additional two invited contributions of review papers, as well as a number of invited seminar presentations at overseas research institutions. The keynote presentations are as follows:

- "The Effect of Parent Phase Strengthening on Shape Memory Behaviour in Ferrous Alloys", Int. Conf. on Advanced Materials, 18B, Tokyo, Japan, 1993 (Publication 17).
- "Martensitic Iron-Platinum Alloys", International Conference on Displacive Transformations, University of Illinois, USA, 1998 (Publication 21).
- "Interfacial Structure and the Shape Memory Effect", SMM'99, Kanazawa, Japan, 1999 (Publication 23).
- "Memory Metals as Smart/Adaptive Materials", TTCP-DSTO Workshop on Smart Materials, Melbourne, Australia, 2001.

Publications 8 and 24 were invited contributions to leading research journals. Within the last eight years, I have presented seminars on martensitic transformation and shape memory alloys at Cambridge University, England; Universiteit Iles des Balears, Spain; Kyoto

University, Japan; University of Tsukuba, Japan; and the Catholic University, Leuven, Belgium. Evidence of my international reputation in this field is apparent in my co-editorship of a special Shape Memory Alloy edition of Metals Forum in 1981; a major role in organizing the International Conference on Martensitic Transformations (ICOMAT) in 1989 in Sydney; and membership of the International Organising Committee of the ICOMAT Conference Series since 1995.

The publications analysed in Section 3.2 clearly demonstrate sustained contributions to fundamental understanding of the crystallography of the martensite transformation and the phenomena of shape memory behaviour. These papers also reveal significant original contributions to knowledge in this field, especially in the field of martensite crystallography. The elucidation of fundamental features of the martensitic transformation in both ferrous and non-ferrous alloys has been used to further the quest for improved shape memory alloys for commercial exploitation. Thus, I have closely linked fundamental and applied research, particularly in the field of development of improved Fe-Mn-Si-based shape memory alloys. I am presently continuing the investigation of this topic, with the funding of an ARC (Australian Research Council) Discovery research grant for the period 2003-2005.

In general, funding for this field of research has arisen mainly from successful ARC or ARGS applications. Dr Noel Kennon and I received funding for research on "Crystallographic and Metallographic Analyses of Shape Memory Alloys" continuously from 1980 until 1988. In addition, I submitted ARC applications for research on iron based shape memory alloys with funding being awarded over the periods 1992-1995, 1996-1998 and currently for 2003-2005. Further grant successes concerned research on melt spun shape memory alloys (1991-1993) and the twin facet model (2000-2003). In all, seven separate applications related to martensitic transformations have been awarded research funding through the Australian competitive grants scheme over a period of about 23 years, an emphatic endorsement of the international competitiveness of my research in this field.

In addition, I was one of four Australian research collaborators involved in a Japan -Australia Monbusho grant co-ordinated by Professor Kazihiro Otsuka of Tsukuba University on the topic of "First Order Diffusionless Phase Transformations on Atomic and

Mesoscopic Scales". Two major workshops were organised through this grant, one in September 1993 in Tsukuba and another in Marysville, Victoria in March 1994. I gave presentations on martensite crystallography based on collaborative research with Professor Otsuka at both of these workshops.

3.3 Welding and Thermomechanical Processing of Steels

My early research in this area involved the interaction of recrystallising ferrite grains with precipitate particles. Publication 1 addresses the nature and origin of the coarse 'pancake' shaped ferrite grains formed in Al-killed steels after cold rolling and batch annealing. The investigation produced quantitative metallographic data on the grain shape anisotropy of the steel both after cold rolling up to 90% and after recrystallisation by batch annealing. Although the grain shape anisotropy was reduced after recrystallisation, it correlated strongly with the slab-shaped grains produced by cold rolling. This type of planar-linear anisotropy (relative to the rolling plane and rolling direction) persisted during substantial grain growth at 700˚C for 80 h following recrystallisation, indicating that the anisotropic grain shape is very stable. The results lend support to the proposal that AlN particles, formed at the grain and sub-grain boundaries of deformed grains prior to the onset of recrystallisation, provide strong barriers to nucleation and growth of recrystallised grains. This 'pinning' effect is particularly strong in relation to grain boundary migration in the direction of the rolling plane normal because of the dense layers of precipitates encountered in this direction. Hence, the shape anisotropy of the recrystallised grains is a result of the anisotropic distribution of pinning particles that, in turn, arises because of the shape anisotropy of the deformed grains. My approach was novel, resulting in elucidation of the recrystallised grain shape (slab-shaped, not 'pancaked') and a valuable contribution to the understanding of the origin of a well known metallurgical effect.

A similar investigation was undertaken during a study leave at the University of Cambridge in 1977-78. I worked in Professor Robert Honeycombe's 'Alloy Steels Group' which had achieved international recognition for studies of interphase (layer) precipitation in steels containing the strong carbide formers: Cr, Mo, V, Nb and Ti [21]. For the most part, the Group's research work was concentrated on high purity laboratory steels in order to eliminate the complexity of the multi-component nature of commercial steels. I worked on such an Fe-C-V steel, studying the effect of interphase precipitation on cold work and recrystallisation of the ferrite grains. The results of this work are presented in Publication 3. Grain shape anisotropy of the recrystallised grains was again observed, but the axis of grain elongation was scattered within $\pm$ 30° of the rolling direction because of the formation of, and recrystallisation within, shear bands formed on cold rolling. The layers of fine interphase precipitates of V_4C_3 existed prior to rolling, but were 'rolled out' into layers approximately parallel to the rolling plane. The precipitates nonetheless homogenised the deformation structure and severely retarded the recrystallisation process. Moreover, the three classical annealing processes: recovery, recrystallisation and grain growth, occurred simultaneously, with the first two processes competing strongly for the available stored strain energy. As a result, a 60% cold reduced sample remained incompletely recrystallised after 1000 h at 706°C.

Following my return to Australia, I initiated research collaboration with BHP Steel on commercial steels microalloyed with V, Nb, Ti or combinations of these elements. Publications 2, 4-7 and 9-12 reflect this concentrated effort to understand the role of alloy carbonitride precipitation on the recovery and recrystallisation of austenite during hot rolling; and on the transformation to, and the mechanical properties of, ferrite produced on subsequent cooling.

Publication 2 reports work on isothermal transformation of deformed austenite in a commercial 0.14%V, low carbon structural steel. The steel was transformed isothermally following austenitisation at 1200 °C and 50% rolling reduction at temperatures in the range 780-820°C. Evidence was found that supported grain boundary bulge nucleation of ferrite, as reported for Nb steels [22]. In addition, 'cascade' nucleation of a layer of fine grains around the prior austenite boundaries was observed and attributed to retarded growth of bulge nucleated grains by V_4C_3 precipitate pinning and subgrain nucleation of new grains ahead of the transformation front. This paper highlights the important principle that transformation to ferrite from deformed austenite is, in effect, a surrogate recrystallisation process driven by both stored strain energy and chemical free energy.

Examination of these concepts is continued in Publication 4, with particular emphasis on the role of interphase precipitation of V_4C_3 on ferrite growth and grain refinement. This paper was a contribution to an international conference on HSLA Steels held in Wollongong in 1984 that I organised in conjunction with Dr Tara Chandra. I was also the principal editor of the Proceedings. The research work described in Publication 4 identified several types of interphase precipitation (IP) as a function of transformation temperature. At higher transformation temperatures ($\geq$ 820˚C), *irregularly* spaced *curved* layers of coarse precipitates are formed by periodic pinning of curved incoherent interphase boundaries $(IPC)_{irreg}$. At temperatures <810˚C, *regularly* spaced *planar* layers of precipitates form at semi-coherent interfaces (IPP). For intermediate temperatures, *regularly* spaced *curved* layers of interphase precipitates $(IPC)_{reg}$. can occur at curved semicoherent boundaries between austenite and ferrite. In all of these cases the layers of particles consist overwhelmingly of a single variant of the Baker-Nutting orientation relationship. Besides defining the distinct types of layer precipitates that can occur and their influence on ferrite growth and the ultimate grain size distribution, the work also established that following transformation to ferrite below about 650˚C, fine multi-variant plates of V_4C_3 can precipitate from supersaturated ferrite, with significant coherency strengthening.

This discovery was put to practical use by analysing the ageing response at 600˚C of three hot rolled steels strip steels microalloyed with V, Nb and V+Nb (Publication 5). All three steels showed a significant age hardening response, indicating that continuous cooling after finish rolling had resulted in ferrite that was supersaturated with the carbide forming element (s). The full strength potential of these steels is therefore not achieved by normal processing, but subsequent ageing can provide a significant boost in strength by means of the formation of coherent multi-variant precipitates of alloy carbide.

The consequences of alloy carbonitride precipitation on grain size distributions in both the austenite and ferrite of commercial Nb, V and Nb-V steels are comprehensively examined in Publication 7. The grain size distributions were found to be skewed in both the austenite and the ferrite, consistent with similar heterogeneous nucleating mechanisms for recrystallisation and polymorphic transformation. The distributions were more complex than uni-modal log normal and can be explained in terms of two overlapping distributions due to intergranular (rim-nucleated) grains and intragranular (core-nucleated grains). It was concluded that the commonly used mean, median and mode values for grain size are poor representatives of the skewness and that means weighted in terms of area fraction, grain volume and interfacial area better reflect the skewness of the distribution. The value of considering these weighted mean grain sizes is that they are more likely to correlate with grain size sensitive properties such as impact toughness and yield strength.

Analysis of the strength of ferrite due to precipitation hardening has been treated in Publication 9. This paper proposes that the common use of the Orowan-Ashby model to predict the strength increment due to precipitation is flawed conceptually since the equation applies to 'dislocation impenetrable', incoherent, spherical particles that are bypassed by dislocation bowing. In contrast, the actual strengthening mechanism must involve shear of coherent plate-shaped particles. Moreover, the fundamental validity of the almost universally accepted concept of additive strengthening effects (due to grain size, solid solution effects, precipitates etc) is also questioned since the strongest resistance to dislocation motion should dominate the yield stress. If the greatest resistance arises from movement of dislocations past precipitate barriers then equations such as Orowan-Ashby should predict the observed yield strength, not the increment.

Publication 10 is an invited contribution to the Bicentennial Issue of Materials Forum, which provides a comprehensive review and analysis of the research that I had led on alloy carbonitride precipitation in commercial microalloyed steels over the preceding eight years. A major conclusion was that the precipitate modes observed in commercially hot rolled steels under continuous cooling conditions are consistent with the modes observed under controlled laboratory rolling conditions and isothermal transformation to ferrite. This work contributed considerable clarification of the mechanisms associated with the different modes of precipitation; and established that deformation of the austenite prior to transformation markedly reduces the precipitate particle size and the sheet spacing.

Although much of the work on microalloyed steels was focused on V-bearing steels, the effect of Nb and Ti additions was also studied. For example, Publication 6 treats Ti-bearing structural steels and reports the development of constitutive equations for the static recrystallisation of these steels during simulated hot rolling. The activation energy for recrystallisation was found to be strongly temperature dependent, with a large increase occurring below 1000°C due to the retarding effect of TiCN precipitation. Equations were developed for predicting the time for 50% static recrystallisation as a function of starting austenite grain size, retained strain and temperature; as well as predicting the recrystallised grain size. Publications 11, 12 and 17 were also concerned with Ti and Ti-Nb steels, particularly the grain coarsening characteristics of austenite on reheating to high temperatures at which dissolution and coarsening of grain pinning TiN particles can occur. The type and morphology of the alloy carbonitride precipitates re-forming in austenite during cooling and deformation by hot rolling were also clarified. Research on austenite grain coarsening and recrystallisation kinetics of Ti, Nb and Ti-Nb microalloyed steels has led to greater understanding of the role of precipitate type and distribution and indicates how to optimise reheating conditions for the hot rolling of commercial microalloyed steels (Publications 6, 10, 11, 12, 17) .

As a consequence of a study leave at the University of Sheffield in 1983, working with the hot working group led by Professor Mike Sellars, I became interested in the effect of Nb on the retardation of recrystallisation of austenite in the finishing stages of hot rolling. Several investigations using transmission electron microscopy of extraction replicas had revealed that NbC precipitates were present after hot rolling [e.g. 23] and it was a widely accepted that NbC precipitation had a strong effect on retardation of austenite recrystallisation [24, 25]. However, since polymorphic transformation of austenite destroys the nexus between precipitation and the deformed austenite structure, there was no direct metallographic evidence of this interaction. To overcome this problem, I proposed the concept of studying an austenitic alloy analogue of a low carbon, Nb microalloyed steel to establish when and where precipitation takes place and whether it produces precipitation hardening of the austenite. The alloy design that I worked on at Sheffield was an 18Cr-8Ni steel containing 0.08% C and 0.05% Nb. Although laboratory hot rolling and plane strain compression studies clearly showed a strong increase in rolling/deforming loads compared to a Nb-free reference alloy, copious precipitation of $Cr_{23}C_6$ had occurred, masking any effect due to NbC.

I subsequently developed a high nickel, chromium-free austenitic alloy in follow-up work at the University of Wollongong and through a PhD research project undertaken by Abdollah-Zadeh we were able to study the interaction of precipitation with the austenite deformation substructure (Publications 13 and 18). The experimental data provided proof that precipitation hardening of the austenite occurred during hot finishing at the lower end of the normal temperature range of 950-850°C. The retained austenitic nature of the alloy allowed a direct metallographic study of the interaction of NbC precipitation with the deformed austenite and the kinetics of its recovery and recrystallisation. The marked reduction in the kinetics of recrystallisation was, for the first time, unambiguously linked with carbide precipitation.

Publication 8, written in 1985, is my first contribution to the field of arc welding of steels. I was the co-supervisor of Wingrove, a PhD student working on a detailed analysis of the Tekken Test for weld cracking susceptibility, with the financial support of the Australian Welding Research Association (AWRA). The restraint stress and the cooling conditions prevailing during the test can result in hydrogen assisted cold cracking (HACC) in the weld metal and/or the HAZ. Publication 8 is one of the first to question the widespread acceptance of weld heat input as the key variable determining the cooling rate and hence the structure and properties of the weld metal and heat affected zone. The heat input HI is evaluated by VI/S, where is a process efficiency factor, V is welding voltage, I is welding current and S is the welding speed. Tekken test welds were carried out using automatic manual metal arc (MMA) welding. The tests showed that the welding control variables: V, I and S, can individually affect the cooling rate and the test cracking behaviour. That is, welds produced with the same nominal heat input can show different cracking susceptibilities corresponding to different sets of values for the three control variables. In particular an increase in welding current, even when balanced by an increase in speed, can exert a strong effect on weld pool dynamics, cooling rate and cracking susceptibility.

Worldwide interest in Cu as an alloying element in high strength structural steels blossomed in the early 1990s and at about this time BHP Steel developed a low carbon, Ti microalloyed steel containing 1%Cu and 1%Ni. Called HSLA 80, this steel was designed as a hot rolled, weldable, 550 MPa min. yield strength steel, similar to A710. The weldability improvement flows from the reduced carbon level (0.05%), and the high strength is achieved by -Cu precipitation hardening. I embarked on detailed investigations of structure-property relationships in HSLA 80, particularly weldability associated with high productivity, high heat input welding which could generate marked strength loss in the HAZ due to Cu solution and/or overageing. Publications 15 and 16 deal with the physical metallurgy of this alloy: isothermal transformation characteristics, structures generated on continuous cooling, age hardening due to precipitation of - Cu; whereas Publications 14 and 21 concentrate on alloy weldability. Publication 14 was an invited review of welding of Cu bearing steels that summarises much of the output of the studies conducted by my research group. This paper demonstrates the outstanding weldability of HSLA 80 and its suitability for military and off-shore structural applications. Guidelines for establishing appropriate welding conditions for HSLA 80 are reported.

A related project on new steel development with Bisalloy Steels led to the successful development of a low carbon, copper-based precipitation hardened Q &T steel of 690 MPa minimum yield strength, with improved weldability over the conventional higher carbon BIS 80 steel [26]. Moreover, tempering at low temperatures results in a yield stress above 1 GPa. Although this project was technically successful, the company does not currently consider that there are any commercial imperatives to market this steel in Australia. However, it provides an insurance policy for the company against possible future competition from imported steels of a similar alloy design that have been developed and marketed in Japan.

Publications 19, 22 and 24 cover a series of projects on the hydrogen assisted cold cracking (HACC) susceptibility of MMA cellulosic girth welds of X80 (550 MPa min. yield strength) pipeline steels. This industrially important work was sponsored by the CRC for Materials Welding and Joining and the Australian pipeline industry. Our project on pipeline girth welds was one of six related projects supported by the industry and Publication 22 is an overview of these six related projects. The collective impact of this raft of projects was a projected saving to the industry in pipeline construction costs of over $100m over the following five year period (L. Fletcher, Executive Director – CRC for Materials Welding and Joining, Annual Report, 1997-8). Publication 22 was selected for the A. Ramsay Moon

Award (shared) by the Welding Technology Institute of Australia (WTIA) for the best technical publication in 1998.

An investigation of HACC in cellulosic welds of X80 steel using the Rigid Restraint Cracking Test is reported in Publication 19. Although HACC is normally considered to require three necessary conditions: the presence of hydrogen; stress concentration; and a 'susceptible' microstructure; this work showed that for high hydrogen content and high restraint, the microstructure does not have to be 'susceptible' for cracking to occur. Hydrogen and triaxial stress can promote intergranular (IG) and transgranular (TG) cracking of the weld metal and the HAZ by microvoid coalescence (MVC) or quasi-cleavage (QC) in microstructures such as acicular ferrite, that are not normally considered to be susceptible. This paper vividly demonstrates the danger of using high hydrogen (cellulosic) electrodes under process conditions that neither minimise restraint nor allow sufficiently slow cooling for substantial hydrogen effusion from the weld region.

Publication 24, "Weld Metal Crack Testing for High Strength Cellulosic Electrodes", reports the first application of the Welding Institute of Canada (WIC) test in Australia to assess the effect of welding heat input, consumable type, restraint and preheat on hydrogen cold cracking in X80 steel. This comprehensive study served to establish operating parameters for crack-free root pass girth welds in high strength pipelines and was awarded the Sir William Hudson prize for the best research publication presented in a WTIA Conference Proceedings or the Australian Welding Journal in 1999.

Publications 20 and 25 consider the welding of low carbon sheet steels, by laser welding (Publication 20) and gas metal arc welding (Publication 25). The evolution of the microstructure in the laser-produced weld zone was investigated in detail, confirming the capability of laser welding to minimise the width of the HAZ and to produce high quality, high strength joints in coated and uncoated sheet steels. Publication 25 addressed the strength loss associated with arc welding of high strength (550 MPa min. tensile strength), zinc alloy coated sheet steels, used extensively in the building construction industry. Since the strength of these low carbon steels is achieved by cold rolling then recovery annealing, the localised heat treatment arising from welding causes substantial strength loss. The project quantified this strength loss for the purpose of structural design of welded components formed from these types of steels. The mechanism of softening was fully elucidated and the interaction of the welding process with the zinc alloy coating was defined. This paper was awarded the Sir William Hudson prize by the WTIA in 2000.

Publication 23 is the product of an invited review of the structural characteristics of low carbon steels. Entitled: " Ferrite Morphology and Residual Phases in Continuously Cooled Low Carbon Steels", this paper provides a unified approach to the morphological interpretation of ferritic products formed in weld metals, weld heat affected zones and wrought low carbon steels during continuous cooling of austenite. Concepts that I have developed over a decade of work on thermomechanical processing and welding of low carbon steels are embodied in this analysis of the transformation products of austenite formed on continuous cooling. The basic morphologies are simplified as either equi-axed chunks or plates and the mechanistic extremes as diffusional and diffusionless transformation. Mixed diffusional-martensitic mechanisms are proposed for intermediate conditions and the various possible types of carbon-enriched, residual microphases are considered in detail.

Some important recent publications were not selected for the purpose of making my case for a DSc because, although accepted for publication, they have not yet been published. These papers have been included in the list of all of my publications in Appendix 2 (A2) and I draw attention to papers 86 and 88 in this list. These contributions concern neural network modelling of the impact toughness of flux cored arc weld metals, as well as the toughness of quenched and tempered pressure vessel steels as a function of postweld heat treatment time and temperature. Successful models were developed not only for predicting toughness, but also for establishing the sensitivity of toughness to typical compositional, microstructural and processing variables.

3.3.1 Standing and significance of research

The research publications discussed in Section 3.3 mostly relate to work conducted in collaboration with an industrial partner, with the objective of improvement of existing technology and its cost-effectiveness. Because much of the work has been industrially funded, the papers listed in this section describe research outputs that are generally more applied than those of research papers presented in Section 3.2. A corollary of this emphasis is that a significant number of the publications discussed in Section 3.3 appeared in proceedings of Australian and international conferences that were open to industrial participation.

I have been involved in research interaction with the Australian companies: BHP Coated Products, BHP Flat Products, Tubemakers and Bisalloy Steels on production of steel sheet and plate for more than twenty years. Although it is difficult to assess the extent of pick-up of research results by the end-users, many of the findings have been incorporated into company engineering know-how and the technology for production of sheet and plate steel products, particularly microalloyed steel products.

Industrial research partners in the steel welding area include Lincoln, Cigweld and Tubemakers; the pipeline industry through the Australian Pipeline Industry Association (APIA); and the power generation industry through the CRC for Welded Structures. Although most of the research funding has come from these industrial and CRC sources, several competitive grant applications to the Australian Research Council (ARC) have also been awarded funding: three ARC Collaborative grants with Bisalloy Steels, BHP and Daniel Brown Gears; and two APA-I grants to support postgraduate research students in welding-related projects. I also wrote a successful application for a Targeted Institutional Links Program (1993-5) with the Joining and Welding Research Institute (JWRI) of Osaka University to collaborate in joining research, particularly using microwave energy. This grant was complemented by a Monbusho Grant from the Japanese side that enhanced and extended the research interaction.

The quality and significance of my research publications in the welding field are reflected in three best research publication awards from the Welding Technology Institute of Australia. My reputation and status are also acknowledged through the invitation by the WTIA to act as Editor of the Welding Research Supplement of the Australasian Welding Journal – a role that I have filled continuously since 1998. I am also a member of the International Editorial Board of the Journal of the Science and Technology of Welding and Joining published by the Institute of Materials (UK).

My standing in the field of the physical metallurgy of welding of steels has led to a long-term research partnership with CSIRO Manufacturing Technology in Adelaide, starting with a GIRD Grant (1988-1990) to study "High Productivity Welding Processes for Australian Plate Steels" ($490,000). A spin-off of this successful research collaboration was the planning and development of an application to establish a CRC in the field of welding technology. I was a core member of the planning and application team that led to the successful bid to establish the CRC for Materials Welding and Joining in 1992. Following this outcome, I was appointed Chairman of the CRC Education Program and, over a three year period, I planned and developed two postgraduate courses on materials welding and joining (Graduate Diploma and Master of Engineering Practice), both of which satisfy the syllabus requirements for external examination leading to the award of the title, European Welding

Engineer (now International Welding Engineer). In the process of establishing this course, I applied for NSW Government funding from the Education Training Foundation and was awarded $150k. At the same time as managing the Education Program, I fulfilled an active research leadership role in a series of CRC funded research projects.

In the overall field of welding and processing of steels, I have received three invitations to present keynote lectures at international conferences and numerous invitations to give seminars at overseas research laboratories. The keynote lecture presentations were:

- "Weldable Copper Strengthened Low Carbon Steels", HSLA Steels '95 in Beijing, China (Publication 14);
- "The Microstructure and Properties of Low Carbon Copper Bearing Steels", International Symposium on New Aspects of Microstructure in Modern Low Carbon High Strength Steels, Iron and Steel Institute of Japan, Tokyo, 1994 [Reference 35 in Appendix 2 (A2)].
- "A Review of the Theoretical and Experimental Background of Hydrogen Assisted Cold Cracking of Steel Weldments", 1st International Conference on Weldmetal Cracking in Pipeline Girth Welds, WTIA-CRC MWJ, Wollongong, Australia, 1999 [Reference 70 in Appendix 2 (A2)].

Within the last eight years, I have presented seminars on the physical metallurgy of low carbon steels at Nippon Steel, Kimitsu, Japan; the Institute for Joining and Beam Technology, Magdeburg, Germany; the Catholic University, Leuven, Belgium; OCAS, Ghent, Belgium; INSA de Lyon, France; Cambridge University, England; and JWRI, Osaka, Japan.

In addition, Publication 10 on alloy carbonitride precipitation in ferrite and Publication 23 on ferrite morphology and residual phases in continuously cooled low carbon steels were invited contributions to Materials Forum, the principal research publication of the Institute of Materials Engineering Australia (IMEA).

Most of my applied research work has been focused on the needs of Australian industry and has involved alloy design and welding and thermo-mechanical processing of steel. It has resulted in significant, original contributions to knowledge of structure-property relationships in welded and processed low carbon steels, as well as providing quantitative models for predicting the behaviour of steels as a result of processing. Moreover, sixteen of the ME and PhD graduates that I have supervised are now working in the Australian steel industry or other metallurgical/materials industries. The general result of this research activity for industry partners has been progressive incremental improvements in product quality and export competitiveness.

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Please see print copy for Appendix 1: Curriculum Vitae

APPENDIX 2: COMPLETE LIST OF PUBLICATIONS

A. Refereed Journals and Conference Proceedings

A1. Martensitic Transformations and Shape Memory Alloys

1. D.P. Dunne and J.S. Bowles, 'Measurement of the Shape Strain for the (225) and (259) Martensitic Transformations', Acta Metallurgica, 1969, 17, p.201.

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PART 4

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