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Metallic structures: A magnificent obsession*

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Professor T.R. Anantharaman, born on November 25, 1927 in Tanjore, Tamil Nadu, received his B.Sc (Hons) degree in Chemistry from Madras University in 1947, the D.I.I.Sc (Metallurgy) from the Indian Institute of Science in 1950, D.Phil and D.Sc degrees from Oxford University in 1954 and 1990 respectively. His professional career includes assignments as Assistant Professor of Metallurgy at the Indian Institute of Science, Bangalore (1956–1962) and Professor of Physical Metallurgy at the Banaras Hindu University, Varanasi (1962–1987). He served as Director, Institute of Technology and Rector at the Banaras Hindu University and as Director of Thapar Corporate Research and Development Centre at Patiala. His original and significant research contributions to X-ray Line Shape Analysis, Metastable Phases and Rapid Solidification span over four decades. He pioneered research in India in every one of these fields. His research findings have been reported in several books and over 200 papers.

Professor Anantharaman is a gifted teacher. His lucid expositions on topics in Metallurgy have inspired and guided generations of students. He has received many honours and awards. Special mention may be made of the National Metallurgists' Day Award (1964), Shanti Swarup Bhatnagar Prize of the CSIR (1967), the Tata Gold Medal of the Indian Institute of Metals (1983), the Distinguished Alumnus Award of the Indian Institute of Science (1985), the Materials Science Prize of the Indian National Science Academy (1987) and the Henry Clifton Sorby Medal of the International Metallographic Society (1989). He has been elected Fellow of the Indian Academy of Sciences, the Indian National Science Academy, the Indian National Academy of Engineering and the American Society for Metals, Honorary Member of the Indian Institute of Metals and Deutsche Gesellschaft fuer Metallkunde and Corresponding Member of the Royal Belgian Academy of Overseas Sciences.

Abstract. The twentieth century has been an exciting and fruitful period for materials scientists involved in probing the structure of metals and alloys at different levels. The Science of Metallography dealing with the macrostructure, microstructure, sub-microstructure and crystal structure of metallic materials has made impressive strides in many directions during this century, particularly during the last four decades coinciding with the author's own research career. The steady advances in optical microscopy, the growing sophistication in electron microscopy and diffraction, the welcome advent of field ion microscopy, the increasing precision in X-ray diffractometry and the powerful back-up provided by Computer Science have all combined to open out many a new and bright vista in Structural Metallurgy in recent decades.

In this lecture some of the notable developments in the fascinating area of metallic structures are highlighted with special reference to the researches of the author, his students and coworkers in several Indian and overseas Laboratories, particularly Oxford (UK), Stuttgart (Germany), Pasadena (USA) and Bangalore, Varanasi and Patiala (all three in India).

Keywords. Metallic structures; science of metallography; computer science.

1. Introduction

I am conscious of the great honour that the Materials Research Society of India (MRSI) has done me by naming me the Distinguished Materials Research Scientist for the year 1992 and would like to start my lecture by thanking Prof. C N R Rao, President of the Society, and his colleagues on the MRSI Council for this, their generous recognition of my modest contributions to Materials Research. The significance of this honour is heightened by the fact that I am following in the footsteps of two senior stalwarts in the field viz., Prof. S Ramaseshan and Prof. E C Subbarao, who have been my friends and well-wishers throughout my professional career. It also gives me a keen sense of satisfaction today to lecture before a highly distinguished audience in this great institution where I started my studies in Metallurgy way back in 1947.

I find it interesting to recall on this special occasion that the three important milestones in my educational career coincided with historic events of considerable national and even international significance. My five-year undergraduate career leading to the B.Sc. (Hons) degree in Chemistry of Madras University had a memorable start with the Quit India Movement launched on August 9, 1942 under the leadership of Mahatma Gandhi. Within a few days of my entering the portals of the Indian Institute of Science here as a Chemistry graduate to embark on this Institute's first-ever three-year course leading to the Diploma (D.I.Sc.) in Metallurgy, our country shook off at long last its colonial yoke and emerged as an independent, sovereign state on August 15, 1947. As I reached London towards end of September 1951 on my way to Oxford to commence my doctorate researches as that year's one and only Rhodes Scholar from India, the glittering Festival of Britain was in full swing, commemorating the centenary of the Great Exhibition of 1851, and I could get a rare insight into the British way of life and characteristics that had enabled Britannia "to rule the waves" for so long.

The Tata Institute, as this famous institution is referred to locally even today in fond memory of its far-sighted Founder, the Late Mr J N Tata, went in a big way after the Second World War (1939–1945) to establish new Engineering Departments. Prof. Frank Adcock, a distinguished metallurgist from the National Physical Labora-

tory, Teddington, England, was invited to establish a Department of Metallurgy here and I was fortunate to belong to the first batch of 12 students admitted to the Diploma course of this new Department in August 1947. As is the usual lot of pioneers everywhere, our batch also had its share of advantages and disadvantages. There was no building yet and a small shed divided into three sections, one for the Department Head, another for the Department Office and the third for a Class Room, was all that we could boast of as our Department for the first two years of our course. We spent considerable time in other Departments and learnt more Chemical Engineering, Electrical Engineering and Mechanical Engineering than was necessary for students of Metallurgy! Such was the paucity of teachers in our own Department that Prof. Adcock, a physical metallurgist, had to teach us all about Iron and Steel Making!! As far as I can recollect, none of the teachers had a first degree in Metallurgy and it was all rather like in the story of the Blind Men and the Elephant, with perhaps this difference that here experts in diverse branches of Metallurgy were making a valiant effort to put together a full-fledged Metallurgist!!!

Let me say in passing that, despite a few problems and some disappointments, I enjoyed every minute of my decade-long association with this Institute, first for three years (1947–1950) as a student, then for a year (1950–1951) as Senior Research Assistant and later for nearly six years (1956–1962) as Assistant Professor of Metallurgy. My father, who was a graduate in Physics and served as Head Master of several High Schools in Thanjavur District, Tamil Nadu, for over two decades, was a great admirer of this Institute. His standard advice to all his bright students was to go in for a degree in Science first and then to join this famous Institute in *any* available discipline. It was therefore no surprise when I became the fourth brother in the family to join this Institute. In fact, my younger brother followed me a few years later and our family went on to set up a few records here. From 1940 to 1962, when I left Bangalore rather reluctantly to take over as Professor of Metallurgy at the Banaras Hindu University, Varanasi, my family could boast of one or two of its representatives all the time here, the 1947–1948 session recording a peak with *three* brothers from my family in three *different* Departments of this Institute! As our country is now all set for family planning norms, it looks as though our family's record of *five* brothers completing courses successfully in *five* different disciplines at this institution will not be broken at all in the years to come!!

As many of you may know, I have gone round the world quite a bit during the last four decades and more, and have been associated for reasonably long periods with truly great and internationally renowned Institutions of Higher Learning and Research like Oxford and Cambridge Universities, England, Max-Planck-Institutes and Hahn-Meitner-Institut, Germany, and California Institute of Technology, Bell Laboratories, and Massachusetts Institute of Technology, USA. All the same, let me tell you today in all honesty and without any exaggeration that no institution in the world has impressed me as superior to this great Institute as a post-graduate institution devoted to teaching and research in diverse branches of Science, Technology and Engineering. The Founder's dream has come true in every respect after over eight decades of steady growth and systematic pursuit of excellence. Of course, there is no room for complacency and all Departments of this great Institute can rise to still greater heights in the years to come. Today it gives me great pleasure to congratulate the staff and students here most sincerely on the many significant achievements of this fine institution. You have every reason to feel happy and proud about your

magnificent inheritance, but you should not forget your duty towards enrichment of this institution's healthy and enviable academic traditions through hard, purposeful and dedicated work.

2. Metals as friends

Having graduated in Chemistry I thought of becoming a Chemical or Extractive Metallurgist during the first year of my three-year course at this Institute. However, the all-pervasive influence of Prof. Adcock first and the effective teaching of Physical Metallurgy later by Dr E G Ramachandran, who joined our Department as Lecturer in 1948 after qualifying for the Ph.D. degree of Sheffield University in England, brought about a gradual change in my attitude in favour of Physical Metallurgy, particularly Metallography and Structural Metallurgy. It so happened that I succeeded this respected teacher of Physical Metallurgy in 1956 when I returned to Bangalore to join here as Assistant Professor after five years abroad, three of them at Oxford and two at Stuttgart, Germany. Prof. Ramachandran's distinguished professional career after 1956 was divided between National Metallurgical Laboratory, Jamshedpur, and the Indian Institute of Technology, Madras. He has been my mentor, friend and well-wisher from my student days and I feel happy to express on this occasion my deep gratitude to him for all his interest, encouragement and assistance during my professional career.

Today there is so much talk of Materials Science, Materials Engineering and Materials Research, as also the emergence of new Materials Departments in many Universities of the world, particularly in America and Western Europe, and new Materials Societies in many countries. Even in conservative United Kingdom a merger of three Learned Societies, each with its Royal Charter, took place a few weeks ago with the formation of a new 'Institute of Materials'. A special issue of the Institute's journal *'Metals and Materials'* celebrated this long-awaited merger with invited articles from former Presidents of the erstwhile Societies. In one of them Sir Alan Cottrell, the present doyen of British physical metallurgists, wrote the following:

"All materials consist of electrons and nuclei, so that ultimately there is only one science, the same for all. However, nature has the ability to magnify small variations into vast differences, ranging for example from the flexibility of rubber to the stiffness of vulcanite, the softness of aluminium to the hardness of alumina, the toughness of brass to the brittleness of glass, the opacity of graphite to the transparency of diamond".

It may surprise many of you here to learn that this unified and wise approach to Materials was simply not there during my student days, not even during my years at Oxford (1951–1954) and Stuttgart (1954–1956). Metallurgy was a discipline by itself; so were Glass Technology, Silicate Technology, Ceramics Engineering, Polymer Science etc. which are today constituents of the unified discipline of Materials Science, Technology and Engineering. As for Metallurgy, it was till the late fifties mostly mineral beneficiation, extractive metallurgy, foundry technology and fabrication techniques, with physical metallurgy struggling to emerge as an important branch of Metallurgy. In fact, I would make bold to say that practically all significant and

fascinating developments in Metallography and Structural Metallurgy, including systematic study of metallic structures at different levels (table 1), structural imperfections of different dimensions (table 2) and crystal structure as well as structural changes (table 3), as also the impact of structural aspects on properties and service behaviour, took place during my four-decade professional career as teacher and researcher in the field of Physical Metallurgy. As is well appreciated by discerning materials scientists of today, it was the extension of the structure-property-service behaviour correlations from metals to non-metals that laid the foundation in late fifties and early sixties for the magnificent edifice that Materials Science has become now.

Thanks to Prof. Adcock and Dr Ramachandran here at Bangalore and to Dr W Hume-Rothery FRS (later Prof. Sir William Hume-Rothery) and Dr J W Christian (later Prof. Jack Christian FRS) at Oxford, I developed a great fascination for metals and alloys from the points of view of their structure, structural changes, structural imperfections and properties, particularly mechanical, from the very early days of my involvement in metallurgical research. The periodic Table of Chemical Elements dominated by metals (figure 1) attracted my special attention and I was

Table 1. Levels of structure in metals (Magnification and resolution indicated).

Level (Magnification and resolution possible)	Instrument	Detail(s) observed
Macrostructure < 25 × , > 40,000 Å	Eye/magnifying glass	Gross arrangement of phases at coarse scale
Microstructure < 2,000 × , > 2,000 Å	Optical/metallurgical microscope	Shape, size and arrangement of phases at a finer scale
Sub-microscopic structure < 800,000 × , > 2 Å	Electron microscope	Fine atomic scale features, such as small particles, precipitates etc.
Crystal structure (in Angstroms)	Electron microscope/X-ray	Arrangement of atoms

Table 2. Possible imperfections in crystals.

Geometrical dimension	Type of imperfection	Examples
0	Point defects	Vacancies, Interstitials, Schottky defects, Frenkel defects
1	Line defects	Edge dislocations, screw dislocations
2	Plane defects	Grain boundaries, stacking faults
3	Volume defects	Pores, inclusions

Table 3. Examples of single crystal structure and allotropy (polymorphism) in metals.**A.** Common single crystal structures in metals (A1, A2 and A3):

Platinum (Pt . . atomic No. 78) . . A1 i.e., *Face-centred cubic* at all temperatures till melting at 1770°C

Tungsten (W . . atomic No. 74) . . A2 i.e., *Body-centred cubic* at all temperatures till melting at 3425°C

Rhenium (Re . . atomic No. 75) . . A3 i.e., *Hexagonal close-packed* at all temperatures till melting at 3130°C

B. Examples of allotropy in metals:

Plutonium: A trans-uranic element with maximum number of allotropes for any metal (Pu . . atomic No. 94)	α . .	Monoclinic till 123°C (16 atoms in unit cell)
	β . .	Monoclinic . . 123–235°C (34 atoms in unit cell)
	γ . .	Orthorhombic . . 235–320°C (8 atoms in unit cell)
	δ . .	Face-centred cubic . . 320–451°C (4 atoms in unit cell)
	δ' . .	Tetragonal . . 451–472°C (2 atoms in unit cell)
	ϵ . .	Body-centred cubic . . 472–640°C (2 atoms in unit cell)
Iron: Most common metal (Fe . . atomic No. 26)	α . .	Body-centred cubic till 761°C (ferromagnetic)
	β . .	Body-centred cubic . . 761–910°C (paramagnetic)
	γ . .	Face centred cubic . . 910–1390°C (paramagnetic)
	δ . .	Body-centred cubic . . 1390–1535°C (paramagnetic)
Cobalt: Known for its stacking faults (Co . . atomic No. 27)	α . .	Hexagonal close-packed till 423°C
	β . .	Face-centred cubic . . 423–1495°C
$\alpha \xrightleftharpoons[\text{cool}]{\text{heat}} \beta$ (α is characterized by stacking faults.)		

(Over 30 metals i.e. nearly half the metals, display allotropy or polymorphism i.e., exist in more than one crystalline form.)

struck by the wide variation displayed by metals even in regard to basic physical properties like melting point and density (table 4). Each metal was soon like a friend to me, each with distinct characteristics of its own.

Since mechanical properties like hardness, stiffness, plasticity (i.e. malleability and ductility), yield strength and ultimate tensile strength have a bearing on the use of metals in large quantities as structural and construction materials, I got interested in due course in the processes of alloying and strengthening pure metals for practical and large-scale applications. The comparative lack of strength in very pure metals was a surprising revelation to me and it was not long before I was fascinated by the vast improvements that could be achieved in the properties of alloys through process like heat treatment, mechanical treatment and thermomechanical treatment (table 5).

Any branch of Science or Technology can advance only through a corresponding progress in instrumentation and experimental techniques to meet its growing needs and sophistication. From the early thirties Physical Metallurgy benefitted considera-

Figure 1. Periodic classification of the elements (including room temperature crystal structures).

Table 4. Wide variation in physical properties of metals.

High melting		Low melting	
A. Melting points of metals (°C)			
Iron(Fe)	1535	Mercury(Hg)	− 39
Titanium(Ti)	1825	Gallium(Ga)	30
Niobium(Nb)	2495	Indium(In)	156
Molybdenum(Mo)	2750	Tin(Sn)	232
Tantalum(Ta)	3010	Bismuth(Bi)	271
Rhenium(Re)	3130	Cadmium(Cd)	321
Tungsten(W)	3425	Lead(Pb)	327
Heavy metals		Light metals	
B. Densities of metals (g/cc)			
Lead(Pb)	11.3	Lithium(Li)	0.53
Mercury(Hg)	13.6	Rubidium(Rb)	1.53
Uranium(U)	19.1	Magnesium(Mg)	1.74
Gold(Au)	19.3	Beryllium(Be)	1.84
Iridium(Ir)	22.5	Aluminium(Al)	2.70
Osimum(Os)	22.6	Titanium(Ti)	4.51

Table 5. Yield strengths of metals and alloys.

Material	Approximate yield strength (pounds per square inch) (psi)
Pure Pb (extruded)	2,000
Pure Fe single crystal	4,000
Pure Al (annealed)	3,500
(99.9%)	
Pure Cu (annealed)	10,000
(99.9%)	
Brass (hard)	60,000
(Cu 60%, Zn 40%)	
Mild steel	40,000
(C 0.2%)	
Stainless steel	1,00,000
(rolled)	
(Cr 18%; Ni 8%)	
Ausformed steel	3,13,600
(C 0.4%; Mn 0.6%; Ni 1.7%; Cr 0.8%; Mn 0.2%; Si 0.3%)	
Metallic glass	6,00,000
Fe ₈₀ C ₇ P ₁₃	
Iron whisker	18,00,000

bly from new instruments, as shown chronologically in table 6. It has given me immense personal satisfaction to note that starting with the electron microscope first constructed in 1931 and proceeding all the way to the scanning tunneling microscope that hit the scientific headlines from 1982, all significant milestones in instrumentation for Physical Metallurgy and Materials Science have been crossed during my life time.

Table 6. Development of experimental techniques in structural metallurgy (1930–1990).

Year	Instrument/Technique	Inventor(s)
1931	Electron microscope (EM)	Ruska
1936	Field emission microscope (FEM)	Mueller
1945	X-ray diffractometry (XRD)	Friedman and Parrish
1949–1954	Thin foil electron microscopy (TFEM)	Heidenreich and Hirsch
1951	Field ion microscope (FIM)	Mueller
1956	Electron probe microanalyzer (EPMA)	Castaing and Guinier
1958	Scanning electron microscope (SEM)	Smith
1963	Television-based image analyser (Quantimet)	—
1967	Atom probe field ion microscope (APFIM)	Mueller
1978	Scanning transmission electron microscope (STEM)	—
1982	Scanning tunnelling microscope (STM)	Rohrer and Binning

Further, it has been my good fortune to take full advantage of many of these new instruments and techniques in different laboratories in India and abroad in the course of my research career stretching back to 1949 at this Institute. I am thrilled even today to examine metallic structural details in relation to a research problem, often amazed and overwhelmed by the range of resolution at my disposal, all the way down from *the hundreds of microns* that my naked eye is still capable of to *tenths of a nanometer* that the atom probe field-ion microscope and the scanning tunneling microscope can manage (figure 2). At this juncture I must also refer to the welcome advent of the Computer Age during my life time and the tremendous support the computers have provided in the solution of structural metallurgy problems. All in all, the last few decades have been a fabulous as well as fruitful period for physical metallurgists and materials scientists. At the personal level I must say that I have come to know and love my friends, the metals, more and more during this period.

3. Imperfections in metallic structures

When I went to Oxford in the autumn of 1951 as the first Indian to work in the Metallurgical Chemistry Laboratories of the already-famous Dr W Hume-Rothery, I did not know that this great scientist was TOTALLY DEAF, this impairment following some terrible ailment during his student days, and yet had achieved so much in life through sheer perseverance and single-minded devotion to research in the area of his own choice. He started his post-doctoral researches at Oxford in the Inorganic Chemistry Laboratory and could develop his Section into a full-fledged Department of Metallurgy during his long and brilliant professional career. When I joined his group in 1951, he was over 50 years, had written a few authoritative books, was a Fellow of the Royal Society and yet was only a *Lecturer* in Metallurgical Chemistry! He became the first George Kelly Reader in Metallurgy around the time I left Oxford in 1954 and still later became the first Isaac Wolfson *Professor* of Metallurgy. In fact, *both* the Readership and the Professorship were endowed by industries specifically for him. In our country we academics seem to expect a promo-

Figure 2. Size scale of metallic structural details as related to instrumentation.

tion every FIVE years and are ready to leave an institution on getting a slightly better position in another institution! How many lessons we can learn from the many-splendoured life of a British scientist like Prof. Sir William Hume-Rothery!!

The Metallurgy Group at Oxford was a rather small one in those days and consisted of a Lecturer (Dr Hume-Rothery), a Research Fellow (Dr J W Christian), who became my thesis supervisor, 4-6 Research Scholars and two supporting staff at the small workshop. The research problems were worked out well in advance and distributed to the Scholars on a first-come-first-served basis. Since I reached Oxford later than

the other English students admitted that year, there was just one problem awaiting me viz., 'Investigations of the martensitic transformation and structural irregularities in pure cobalt'. It was no reflection on the training I received here in Bangalore, but I did not honestly know then that a pure metal like cobalt could undergo a martensitic or shear transformation. Nor did I have any clue as to the nature of the structural irregularities in hexagonal cobalt!

Looking back, I think I was extraordinarily lucky to have Dr Christian as my doctoral guide. He was a brilliant scientist, an understanding supervisor, an unassuming person and a perfect gentleman. Soon enough I became familiar with imperfections in metallic structures like vacancies, dislocations, stacking faults and inclusions (see table 2), which were to figure prominently in metallurgical research during the next few decades. Of course, every student of metallurgy knows today that, despite their rather small presence in relation to the total volume of the solid, these structural irregularities have a profound influence on the mechanical behaviour of solid metals and alloys.

For over a decade and at different places like Oxford, Stuttgart, Bangalore and Varanasi, structural irregularities in general and dislocations and stacking faults in particular loomed large in my research efforts. Since these two types of defects affect X-ray reflections in several ways and thus are amenable to study by the X-ray diffraction technique, I could make some significant contributions, along with my students and coworkers, to theoretical treatment of X-ray diffraction effects of these structural irregularities, as also to their practical application for experimental evaluation of these crystalline imperfections in metals and alloys.

My earliest contribution in this field emerged during my doctorate work at Oxford and dealt with a new method for measuring integral breadths of X-ray reflections. Subsequently, a general method of analysis for the separation of domain size, lattice strain and stacking fault contributions from X-ray line breadths of face-centred cubic (fcc) metals was developed by my group at Varanasi. A modified Fourier method of analysis was also developed by the same group, using a single X-ray diffraction line to overcome the limitations of the well-known Warren-Averbach method requiring multiple orders of X-ray reflections.

Those who are familiar today with different types of intrinsic and extrinsic stacking faults in close-packed metallic structures will be somewhat surprised to learn that at the start of my doctoral work at Oxford only one type of such faulting viz. the so-called growth faults in hexagonal close-packed (hcp) cobalt, was known and identified as such in literature. It was during my Oxford work that I postulated for the first time and also established reasonably convincingly the coexistence of *both* growth and deformation faults in hcp crystals. Later at Varanasi my group dealt with a third type of fault viz. extrinsic fault, in hcp metallic structures and developed the necessary X-ray diffraction theory.

Another important milestone was crossed in this area by the Varanasi group in the late sixties. Possible fault configurations in the so-called double hexagonal close-packed (dhcp) crystals were worked out and the X-ray diffraction effects were also calculated for each type of faulted structure. A number of plastically deformed metals and alloys and, for the first time, rapidly solidified non-equilibrium alloys were subjected to X-ray diffractometric studies for different types and combinations of imperfections by the Varanasi researchers, most of these my Ph.D. students. Such X-ray studies encompassed a large number of pure metals with fcc, hcp, dhcp and

body-centred cubic (bcc) structures and also alloys crystallizing in these structures under equilibrium or non-equilibrium conditions.

The tremendous progress made in about two decades in our understanding and appreciation of faulting in close-packed metallic structures is most impressively brought out in tables 7–9 prepared by my colleagues and coworkers at Varanasi around 1972. This profusion of different types of stacking faults has to be compared with the situation at the beginning of my Oxford days when only the growth faults in hcp cobalt were known! It is difficult to believe that a few researchers in the ancient city of Varanasi known essentially for its Spirituality could make a significant contribution to Science through their decade-long involvement with structural irregularities in metals and alloys!

Table 7. Common close-packed structures and their notation.

Name	Number of layers	Stacking sequence	Jagodzinski notation	Ramsdell notation	Hexagonality
hcp	2	AB,A	h	2 H	1
fcc	3	ABC,A	c	3 R	0
dhcp	4	ABAC,A	hc	4 H	1/2
—	6	ABCACB,A	hcc	6 H	1/3
—	8	ABABACAC,A	hhhc	8 H	3/4
—	8	ABCBCBCB,A	hccc	8 H	1/4
sm-type	9	ABCBACAB,A	hhc	9 R	2/3
—	12	ABCACBCBCAB,A	hhcc	12 R	1/2

(hcp-hexagonal close-packed; fcc-face-centred cubic; dhcp-double hexagonal close-packed; Sm-samarium-type)

Table 8. Comparison of the fcc, hcp and dhcp structures.

Feature	fcc	hcp	dhcp
Number of atoms in the unit cell	4	2	4
Atomic coordinates	(000; $0\frac{1}{2}, \frac{1}{2}, 0$; $\frac{1}{2}, \frac{1}{2}, 0$)	(000; $\frac{1}{3}, \frac{2}{3}$)	(000; $\frac{1}{3}, \frac{2}{3}, 0$; $0, 0, \frac{2}{3}$)
Ideal c/a ratio	1	$\sqrt{8/3}$	$\sqrt{32/3}$
Stacking sequence	cccc ...ABCA...	hhh ...ABA...	chchc ...ABACA...
Indices of the stacking plane	(111)	(0002)	(0004)
Distance between stacking planes	$a/\sqrt{3}$	$c/2$	$c/4$
Displacement of B and C positions with respect to A	$(a/6)\langle 11\bar{2} \rangle$	$(a/3)\langle 10\bar{1}0 \rangle$	$(a/3)\langle 10\bar{1}0 \rangle$
Number of possible stacking faults	2 intrinsic 1 extrinsic	2 intrinsic 1 extrinsic	7 intrinsic 2 extrinsic

Table 9. Stacking faults in fcc, hcp and dhcp structures.

Crystal structure	Type of fault	Stacking sequence	Process of formation
fcc	Intrinsic-2h (Deformation)	cchhccc ABCBCAB	Shear or removal of 1 layer
	Extrinsic-hch (Double deformation)	cchchcc ABCBABC	Double shear or insertion of 1 layer
	Intrinsic-h (Growth or twin)	cchccccc ABCBACB	Twin or successive glide
hcp	Intrinsic-2c (Deformation)	hhcchhh ABACBCB	Shear
	Intrinsic-c (Growth)	hhchhhh ABACACA	Removal of 1 layer + glide
	Extrinsic-3c	hhccchh ABACBAB	Insertion of 1 layer
dhcp	Intrinsic-ch (Deformation)	chcchhchc ACABCBCAC	Shear
	Extrinsic-4c (Double deformation)	chccccchc CACBACBAB	Double shear
	Intrinsic-3c	chccccchc ACABCABAC	Removal of 1 layer
	Intrinsic-h (Growth 1)	chchhchch ACABABCBA	Removal of 1 layer + glide
	Intrinsic-2h	chchhhchc ABACACABA	Removal of 2 layers
	Extrinsic-hcc	hchhccchc CABABCABA	Insertion of 1 layer
	Intrinsic-3h	chchhhhch ACABABABC	Insertion of 1 layer + glide
	Intrinsic-c (Growth 2)	chcchchch ABACBCACB	Insertion of 1 layer + glide
	Intrinsic-2c	chccccchc ABACBABC	Insertion of 2 layers + glide

4. Structural changes in metals and alloys

In the Oxford metallurgy tradition Dr Christian blazed a new trail by taking his first two research scholars, myself and my good friend Mr Z S Basinski from Poland (presently Prof. Basinski FRS, of Mac Master University, Canada), to work on phase transformations or structural changes, particularly on martensitic transformations. When a new room was added in 1952 to accommodate the three of us, it was referred to in a light vein as 'The Dislocation Hut' that housed 'The ABC of phase transformations', the first letters of the alphabet coming from our names! The very first paper of my research career thus dealt with the macroscopic shear in the phase transformation in cobalt, but my interests shifted soon to the nature, origin and impact of stacking faults in hexagonal cobalt. However, a decade later I was attracted again to structural changes in both ferrous and non-ferrous alloys.

I need not stress to the distinguished audience here that a knowledge of phase transformations in general and of structural changes in the solid state in particular, constitutes today the solid foundations for the science and technology of alloy

development and processing that has evolved gradually over the last five decades. Collaboration with scientists in Varanasi, Stuttgart, London, Leuven and San Diego enabled me to make some contributions in this area, particularly through establishment or refining of binary phase diagrams, structure determination, study of precipitation phenomena in aluminium alloys and investigation of tempering responses in low-alloy steels. I shall refer here only to a few investigations which were both fascinating and fruitful.

Among binary phase diagrams, the manganese-gallium system is characterized by the combination of a very high melting metal (Mn) with a very low melting metal (Ga). Working during a summer vacation with German researchers in the Max-Planck-Institute at Stuttgart, I could get acquainted with eight peritectic, three eutectoidal and two peritectoidal reactions as well as ten different intermetallic phases in this rather complex phase diagram (see Meissner *et al* 1965).

Let me now recall my enjoyable and fruitful two-week visit to the beautiful La Jolla Campus of the University of California, San Diego, when I was asked as a metallurgist by some physicists to explain some complexities in electrical resistivity and superconductivity data on annealing some cadmium-mercury alloys at sub-zero temperatures. My intuition worked well in that salubrious and congenial Californian climate and I was able to identify the unusual order-disorder transformations at CdHg_2 and Cd_2Hg compositions (figure 3). We wrote a fine paper before my fortnight's stay ended at San Diego, and I got the letter accepting this paper for publication in '*Acta Metallurgica*' (see Claesson *et al* 1966) before my visit to USA was over!

The allotropy of pure cobalt with its two close-packed structural modifications viz. face-centred cubic (fcc) *above* 420°C and hexagonal close-packed (hcp) *below* that temperature, and the possibility of the emergence of faults in the stacking of the close-packed layers in the latter, has had a special fascination for me since my doctoral years (1951–1954) at Oxford, UK. There have been speculations off and on in scientific literature about a body-centred cubic (bcc) modification as well in pure cobalt just below its melting temperature, although there has so far been no convincing proof for this $\text{fcc} \rightleftharpoons \text{bcc}$ structural change at higher temperatures, as available in case of the metals iron and manganese. Thus I was rather surprised to come across a research

Figure 3. Unit cells of the disordered and ordered phases of Cd–Hg. (a) ω phase, disordered; (b) ω' phase, ordered, formula Cd_2Hg ; (c) ω'' phase, ordered, formula CdHg_2 . The dimensions of the ordered cells (b) and (c) are such that they can be duplicated exactly by the stacking of three units of the disordered cell (a). All three unit cells are body-centred tetragonal.

publication during a summer visit to the Catholic University at Leuven, Belgium, reporting on a rather complex allotrope of cobalt with a hexagonal structure featuring a somewhat large unit cell ($a = 8.29 \text{ \AA}$; $b = 10.54 \text{ \AA}$; $c/a = 1.272$) with 46 atoms in it. This unusual crystalline modification was apparently produced during spark erosion of pure cobalt in air. Concentrating on the conditions of the experiment and the affinity of cobalt to nitrogen and carbon, I was able to show that the concerned investigators had mistaken X-ray reflections from the complex interstitial compounds of cobalt as arising from the metal itself and they had arrived at a rather large unit cell and complex structure for a metal characterized by two comparatively simple crystalline modifications (see Anantharaman 1970).

I have had an abiding interest in the study of precipitation hardening in aluminium alloys, partly because of the vast resources of bauxite and the high potential for aluminium alloy development and use in our country. The aluminium-zinc system had a special fascination for me in view of its two rather intriguing peritectoid reactions involving α , α' and α'' fcc solid solutions and the other β hcp terminal solid solution. In fact, I have drawn some parallels in one of my lectures (see Anantharaman 1974) between the $\alpha' \rightleftharpoons \alpha + \beta$ monotectoid transformation of this system and the transformation attempted in the Indian Yoga tradition in the human mind or the mental being of Man. Extensive investigations of the precipitation reactions in Al-Zn alloys at Varanasi led my students and me to a study of side-bands in X-ray patterns and the spinodal decomposition in some of these alloys and to the establishment of the metastable solvus as well as coherent spinodal curves in this alloy system (figure 4). On a short visit later to Imperial College, London, I could examine isothermal decom-

Figure 4. The metastable solvus and coherent spinodal curves in the Al-Zn system. (—, equilibrium curves; — — —, metastable solvus (G.P. zones); — · — · —, metastable solvus (R-phase); —, coherent spinodal (G.P. zones); · · · · ·, coherent spinodal (R-phase)).

position data for some Al–Zn alloys as obtained in the million volt electron microscope (MVEM) there and connect them up effectively with our Varanasi data. Thus a satisfactory explanation could be arrived at for the observed growth rate in the cellular reaction in Al–Zn alloys, based on Turnbull's theory of cellular reaction as controlled by cell boundary diffusion and influenced by continuous precipitation in the matrix (see Anantharaman *et al* 1974).

5. Structure of rapidly solidified alloys

Metallurgists in India and abroad know that for the last two decades my first love in research has been reserved for rapidly solidified metallic materials viz. metallic glasses, microcrystalline alloys and quasicrystals. It was during an extended visit to the laboratories of Prof. Pol Duwez at the California Institute of Technology, Pasadena, USA, that I fell in love with the unusual products of rapid solidification (at cooling rates approaching and exceeding 10^6 K/s) and felt strongly, despite the views of Prof. Duwez to the contrary, that these had definite technological and commercial potential. It was my good fortune to pioneer research in this fast-expanding area in our country with the enthusiastic involvement of a few brilliant researchers at Varanasi. In the exhilaration of our fruitful and satisfying work in this area, we did not then realise that the BHU Metallurgy Laboratories at Varanasi were among the first SIX institutions in the world to make a mark in this new field of research. It was no surprise therefore that within two decades of this auspicious beginning at Varanasi during the 1966–1967 academic session, apart from over 200 publications, the Varanasi group produced three books dealing with developments in this area viz. "Rapidly Quenched Metals: An Annotated Bibliography" (Plenum Press, 1981), "Metallic Glasses: Production, Properties and Applications" (Trans Tech Publications, 1984) and "Rapidly Solidified Metals: A Technological Overview" (Trans Tech Publications, 1987).

Briefly stated, the numerous contributions of the Varanasi group to the study of rapidly solidified metals and alloys have been in the following diverse areas:

- (a) Development of techniques for rapid solidification at cooling rates in the $10^4 - 10^8$ K/s range.
- (b) Estimation of cooling rates.
- (c) Production of new non-equilibrium phases.
- (d) Determination of crystal structures through X-ray and electron diffraction techniques.
- (e) Study of microstructure and substructure.
- (f) Construction of metastable phase diagrams.
- (g) Theoretical approaches to predict formation of metastable phases, particularly metallic glasses and quasicrystals.
- (h) Production and characterization of metallic glasses.
- (i) Production and characterization of quasicrystals.
- (j) Development of technology for production of soft-magnetic metallic glass tapes.

I need not go into details here, as these contributions have been made in recent years and are generally known to knowledgeable persons like those in this audience.

Presently at the Thapar Corporate Research and Development Centre at Patiala,

I am engaged along with my research students in X-ray studies of Al–Cu–Fe quasi-crystals, trying to explain their formation and crystal structure with traditional concepts, and in development of new Ag–SnO₂ electrical contact materials through better understanding of the microstructure-property relationships in them. I still experience a thrill when I start the study of a new metallic material. It is like making a new friend, who has the potential to enrich your life.

Many people ask me: “How long will you go on with your study of metallic structures? Is it not becoming an obsession?” “Yes”, I say in reply, “but what a magnificent obsession!” – and I mean it.

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