Chapter 1:

Wootz Steel as the Acme of Mankind's Metallurgical Heritage

"Wootz was the first high-quality steel
made anywhere in the world. According
to reports of travelers to the East,
the Damascus swords were made
by forging small cakes of steel that
were manufactured in Southern India.
This steel was called wootz steel.
It was more than a thousand years before
steel as good was made in the West."

-J. D. Verhoeven and A. Pendray, Muse, 1998

What is Wootz? Its Place in the History of Technology

The school or college going student today may not be aware that India's contributions and prowess in the making of iron and steel were amongst the most remarkable in the ancient world. Of course, many of them may have had the occasion on school tours to visit the imposing Qutb Minar Complex in New Delhi and to admire the splendid Gupta era Iron Pillar (ca 400-420 AD). It stands as a monument to a glorious Indian tradition in the field of ferrous metallurgy. The Iron Pillar, the earliest and the largest surviving iron forging in the world, is regarded as a metallurgical marvel because it has defied the laws of corrosion of iron even after so many centuries, earning the nickname, the 'rustless wonder'. However, the Iron Pillar is not the only testimony that there is to the skills of ancient Indian iron and steel metallurgy.

There is another truly remarkable story that is not so well known. This is the chronicle of the legendary wootz steel from India, which has long been a subject of much fascination around the globe, with many legends and accounts surrounding it. This book highlights the fact that India led the world in developing an impressive tradition more than two milennia ago of making high-grade steel in South India, known as wootz.

But what is this strange word, wootz? The term was coined, when European travellers from the 17th century onwards came across the making of steel by crucible processes in Southern India in the present day states of Tamil Nadu, Andhra Pradesh and Karnataka. Wootz was the anglicization of 'ukku', the Kannada word for steel.

The fame of steel from India is well captured in the words of the Arab Edrisi (12th century) who commented that:

'the Hindus excelled in the manufacture of iron and it is impossible to find anything to surpass the edge from Hinduwani or Indian steel'

Wootz steel has also become synonymous with Damascus steel since it was used to make the fabled Damascus swords. Figure 1 shows a magnificent dagger dating to 1585 from Mughal India. The blade has an increased thickness near the point for penetrating enemy armour. Emerald and rubies adorn the gold hilt. The fine wavy pattern added a sense of beauty to the fear of the sword.

The significance of this book to the history of technology lies in the fact that although Indian wootz was such an important material in the metallurgical history of mankind there are no books by Indian authors on this subject. Also the context of wootz steeel in the historical evolution of materials in India has not received adequate emphasis so far. There are some books related to Damascus steel and blades, often focussing on the fine collections of Persian or Arab armoury. Instead of adopting a scholarly presentation usually associated with research monographs in archaeometallurgy, this book has been oriented towards a wider readership inclusive of school and college students. Thus, a style comparable to popular articles such as those appearing in 'Scientific American' has been adopted. References have not been inserted in the text. However, the name of the author from whose book or paper the matter has been paraphrased has been indicated with the sources given under suggestions for further reading. Furthermore, to make the book more reader friendly, colour illustrations with a historical content have been specially commissioned from Paul Fernandes, who has previously illustrated a light-hearted book on 'Bangalore' by Peter Colaco. While this book does not purport to be exhaustive, it will have achieved its objective if it ignites interest in steel in general and wootz steel in particular.

Archaeometallurgical, Historical and Metallurgical Significance

Chapter 2, entitled 'The Three Ages of Civilisation: The Stone, the Bronze and the Iron Ages', gives a brief global history of materials in relation to wootz steel. C. J. Thomsen first pointed out in 1836 that the civilisational march of mankind is closely identified with the materials in dominant use at a given historical period. He suggested that the division into the three ages – stone, bronze and iron – captures this progress over ten millennia. The beginning of the uses of the eight metals of antiquity makes for a thrilling account. Two other key materials, silk and diamond, originating from China and India respectively are briefly touched upon. It may be pointed out that the coming of the Age of Iron had the biggest impact on the fortunes of mankind and even today iron is the most used metal.

The emergence of wootz steel marked the coming of the Age of Steel. This is emphasised in Chapter 3 on 'Steel and the Sword'. While it is ironic that Benjamin Hunstman in Sheffield in 1740 is credited with developing the process of crucible steel production, it is quite likely that he took his cue from some of the processes of crucible steel making in India described by the European travellers of the 17th and early 18th century. In 1855 Sir Henry Bessemer invented the converter, named eponymously after him, and ushered in the Age of Steel. The possibility of making steel in tonnage quantities revolutionized technology and made the Industrial Revolution possible. The alloying of iron with carbon leads to wrought iron, low and high carbon steels and cast irons. The rich variety of phases and microstructures obtained by composition control and variations in processing are briefly elucidated. Steel still rules as perhaps the most important modern material.

Swords have held sway over the human imagination for nearly two millennia. As the sword can be used in close combat, it became an extension of the warrior. The types of swords used in different parts of the globe are described in Chapter 3. In due course of time the development of gunpowder, cannon and guns led to the relegation of the sword to ceremonial purposes.

A fascinating historical perspective is that the tale of wootz steel is woven into so many important legends and accounts of major battles and cross-cultural interactions in history. This is captured in the Chapter 4, entitled 'Romance of Wootz Steel and the Damascus Sword'. This chapter also touches on the origins of the term wootz. The meaning of the Arabic-inspired term Damascus in connection with the magnificent swords made of wootz steel is also explored. The dramatic moments in history linked to wootz range from Alexander's Indian encounter with Porus, to the Crusades between the Christian West and Islamic Middle East. Wootz is thus celebrated in novels, poems and movies.

Historically speaking, much has been written about Indian wootz steel by the travellers from Italy, France and England. This is reviewed in Chapter 5 entitled 'Crucible Steel and Indian Armoury: Sixteenth to Nineteenth Century Accounts'. These provide evidence that wootz steel was made by crucible processes over a fairly vast geographical area of Southern India over nearly half the size of Europe in a large semi-industrial enterprise with shipments of tens of thousands of wootz ingots being sent to places such as Persia. India was not only known during this period for its mastery in making the raw material of steel, but was also highly reputed for its swordsmithy as exemplified by accounts of the unsurpassed excellence of a swordsmith of Thanjavur.

Tipu Sultan who hailed from the land of wootz in Mysore and in whose domain wootz steel as well as Damascus blades continued to be made was a formidable opponent of the British in the late eighteenth century. The fabled 'Sword of Tipu Sultan' is an Indian artefact which is not only a testimony to Indian skills in ferrous metallurgy, but has also captured the public imagination as an incandescent symbol of Indian resistance to colonial British rule. Wootz steel can also be seen as a leitmotif for the Indian freedom struggle against the British. It is said that following the Indian Sepoy Mutiny of 1857 the British set about destroying scores of wootz blades.

Quite apart from this rich historical significance, wootz steel has a unique place in the annals of science. It played a pivotal role in spurring developments in 19th century metallography and metallurgy. The best-known scientists of the time such as Michael Faraday, Jean Robert Breant and Pavel Anossoff investigated and characterised it. This is elucidated in chapter 6, entitled 'European Excitement: Sixteenth to Early Twentieth Century Experiments'. In fact, in many ways, this phase paved the way for the spectacular materials revolution, which is associated with the twentieth century indirectly leading to the development of alloy steels. One could even claim that but for this, many of the inventions of our time from trains to aeroplanes, which we take for granted might not have come into vogue when they did.

In the early decades of the twentieth century wootz steel and the Damascus sword ceased to be objects of intense interest. But with the initiative of the Cyril Stanley Smith interest in wootz was revived. In the latter half of the twentieth century the pursuit moved across the Atlantic to the USA. Oleg Sherby and Jeff Wadsworth found that the material exhibited superplasticity, while J. D. Verhoeven showed that minute quantities of vanadium led to the pattern created by the carbides. The extinction of this steel making process in India was attributed to the depletion of vanadium containing iron ores. It is also interesting to note that many of the investigators have often differed sharply in their conclusions and fought vigorous duels in the pages of the scientific journals. These aspects are discussed in chapter 7, entitled ‘Replication of Wootz: Twentieth Century American Adventures’

A distinction may be made between true Damascus blades in which the layered wavy light-and-dark pattern was an intrinsic property of etched wootz steel and pattern-welded Damascus blades in which patterns were created by welding layers of lower and higher carbon steel such as the Samurai swords of Japan. Chapter 8 entitled ‘On Pattern-welded Damascus Blades: Imitation as the Best Form of Flattery’ discusses the process of pattern-welding and pattern-welded Damascus blades which were sometimes mistaken for true Damascus blades. Examples of both true Damascus steel and pattern-welded Damask steel are known from India.

In recent times it is exciting to note that scientific studies of archaeological materials are throwing new light on the problems of archaeology and history of art. The subject of archaeometallurgy is concerned with the study of ancient metallurgy. It enhances our understanding of issues in archaeology and history of technology and is still an emerging discipline in the Indian context. Chapter 9 ‘Archaeometallurgy of Wootz Steel: A Beginning without an End’ explores some of the archaeometallurgical evidence for wootz steel. While there is literary evidence such as the Roman accounts of iron from the Seres, which may be linked to the Southern Indian region, much awaits to be uncovered in the archaeometallurgy of wootz in India.

The pioneering contributions of K. N. P. Rao in the identification of several sites, where crucible steel making was practised, are highlighted. Significant studies have been made by the American Thelma Lowe of Deccani wootz crucible steel sites. Recent work on archaeometallurgy of wootz steel from the Indian side has come from Sharada Srinivasan’s findings of previously unknown sites in Tamil Nadu and Karnataka related to crucible steel production. This chapter also incorporates a narrative -‘The Road to Mel-siruvalur’- to convey to the young readers the sense of adventure and challenge, and the rewards of undertaking archaeometallurgical research. In recent years concerted and well-funded archaeometallurgical studies have been undertaken by smaller countries such as Sri Lanka, Turkmenistan and Uzbekistan in collaboration with international teams. Gill Juleff and Ann Feuerbach have made important contributions. Their studies established that crucible processes thrived in these places by about 1000 AD. This has significantly expanded the known geographical horizons of crucible steel to make it a pan-Asian technology.

At the dawn of the third millennium, it may come as a surprise that despite the intense scrutiny that wootz steel and the Damascus sword have been under for over three centuries, there are still a few secrets to be uncovered. This aspect is highlighted in chapter 10, entitled 'Ancient Steel Meets Modern Science: Twenty First Century Advances', which discusses contemporary studies. In a recent article German investigators have shown that part of the exceptional combination of properties may be due to the occurrence of iron carbide as a nanowire. Greg Olson has tried to replicate the wootz steel and the resultant product by starting to design from first principles. Thus wootz has an enduring significance even in this modern age of silicon, nanomaterials and quantum mechanics.

Renaissance of Indian Iron and Steel Industry: The Legacy of the Tatas

From about 300 BC to the 17th century, India enjoyed prosperity and fame as a centre for the production of steel, exporting it across the world. The British colonial rule saw the decline of this activity. It was left to the visionary Jamsetji Nusserwanji Tata (Figure 2), hailing from a business family of Zoroastrians, to revive this tradition of steel making. He pioneered the idea of starting the first modern steel plant in India towards the closing years of the nineteenth century. The British were sceptical about Indians producing steel by modern methods. The sheer indomitable will of Tata saw the realization of this dream in 1907 breaking the bonds of mortality as Tata passed away in 1904. The British disdain that Tata had to overcome can be gauged from a comment by Sir Frederick Upcott, Chief Commissioner for Indian Railways, 'Do you mean to say that the Tatas propose to make steel rails to British specifications? Why, I will undertake to eat every pound of rail they succeed in making'. Before he passed away in 1904, Tata laid down specifications for the building of India's first industrial steel plant at Jamshedpur, now in the state of Jharkhand. Tata Steel was established in 1907, headed by his son Sir Dorabji Tata. In fact, Dorabji Tata was later to comment wryly that 'Sir Frederick Upcott would have had a slight bout of indigestion' since Tata Steel went on to ship 1500 miles of steel rails to Mesopotamia during World War I!

Thus the story of the history of steel in India is also significant because its resurgence in the modern period is tied to the story of the House of Tata whose success in business has been matched by philanthropic and social concerns. The year 2004 is memorable because it marks both the death centenary of J. N. Tata whose efforts led to the founding of the Indian Institute of Science, Bangalore in 1909 and Tata Steel in 1907, as well as the birth centenary of J. R. D. Tata, founder of the National Institute of Advanced Studies, Bangalore. The inspiration for the founding of these institutions can be traced back to a historic letter of 1898 from J. N. Tata to Swami Vivekananda, India's great spiritual thinker and reformer. The letter indicates that their meeting on a boat to America, when Swami Vivekananda was on his way to address the world congress on inter-faith harmony, and had inspired Tata to strive towards the establishment of an institution for the cultivation of the natural and humanistic sciences.

Amongst the eclectic influences on J. N. Tata were the words of Thomas Carlyle that ‘The nation that gains control of iron soon gains control of gold’. This propelled him towards setting India’s first industrial iron and steel plant. It is also an interesting dimension that a landmark book on the traditional iron smelters of Central India, the Agaria, by the renowned English anthropologist Verrier Elwin was supported through J. R. D. Tata’s efforts and dedicated to him. As 2004 marks the centenaries of these leading lights of the House of Tata, it appears to be an opportune time to recall India’s great accomplishments in the field of wootz steel as a source of inspiration and confidence for future generation of metallurgists in India and elsewhere.

Wootz Steel as an Eastern Contribution to Global Science

It is generally acknowledged that from the beginning of civilisation up to 1800, the knowledge of materials and the mastery over their composition was more advanced in the Far Eastern cultures, such as Indian and Chinese, than in Western cultures. Cyril Stanley Smith has speculated that this may be due to the Eastern emphasis on aesthetics. An example is the superb Chinese ceramics, which invaded Europe in the sixteenth century. The beautiful Chinese-ware inspired European attempts to replicate them. Similarly the attempts to duplicate the fascinating texture of the Damascus Sword led the Europeans to the discovery of carbon in steel, an appreciation of microstructure and indeed the foundations of modern materials science. Smith remarked that man assays metals. However, metal can just as well be used to assay the progress of mankind. In this assay, and especially in the use of iron and steel in antiquity, the ancient civilisation of India acquits itself with glory. This book narrates this remarkable contribution of an Eastern material to global science.

This book sets out to capture the romance and adventure of the tale of wootz steel of how the Indians were the world leaders in antiquity in the manufacture of this legendary high-grade steel, which was highly prized and much sought after across several regions of the world over nearly two millennia. It appears fair to claim that wootz steel as an advanced material dominated several landscapes: the geographic landscape spanning the continents of Asia and Europe; the historic landscape stretching over two millennia as maps of nations were redrawn; the literary landscape as celebrated in myths and legends, poetry and drama, movies and plays, and, not least of all, knitting together the religious landscape through trade and other interactions of Hinduism, Buddhism, Zoroastrianism, Judaism, Islam and Christianity. This is unique as no other advanced material can display this mutifaceted splendour.

Chapter 2:

The Three Ages of Civilization: The Stone, Bronze and Iron Ages

Gold is for the mistress- silver for the maid
Copper for the craftsman cunning at his trade
"Good" said the Baron, sitting in the hall,
" But, Iron- Cold Iron, - is master of them all".

-Rudyard Kipling

The Three Age System, an Archaeological Revolution

Materials are synonymous with human civilisation. Artefacts made of materials for both artistic and utilitarian purposes dominate every day life. With the passage of time they have become increasingly sophisticated. It is intriguing to observe that just as man has evolved through the Darwinian process of biological evolution with the survival of the fittest, materials have also gone through a process of evolution, inanimate though they are. Thus, at different periods of history one set of materials was in predominant use only to give place at a later time to a more advanced material. Different stages in this evolution have been christened as the Stone Age, the Bronze Age and the Iron Age. This classification system is relatively recent and was devised by the Danish curator of museums, C. J. Thomsen in 1836 for the sequence of technological periods (stone, bronze, and iron) in Old World prehistory. It established the principle that by classifying artefacts, one could produce a chronological ordering. In reality, the technology of iron smelting was developed at different times throughout the Old World, and in some cases, as in parts of the African continent, the Bronze Age was entirely skipped. In the Americas the age of gold and even platinum flourished, until it was shattered abruptly by the invading Spaniards with iron and steel.

The time line of material evolution captures some key events in the evolution of materials (Table 1). This must be considered as illustrative, as new knowledge derived from archaeometallurgy continually refreshes our knowledge in this area and alters the dates. Silk has been added to this list as it is another material from antiquity which linked religions, nations and historical periods in an extraordinary way through its trade on the Silk Road. Diamond has also been added, as it has a dazzling Indian connection. The table ends with 1856, when the advent of tonnage steel by the Bessemer converter brought about a tectonic change in the use of materials. From the discovery of naturally occurring metals and materials there was a passage to deliberately engineered materials with an astounding combination of properties. Indeed, the ever-accelerating pace of development of engineered materials also leads to new machines and devices marking quick social changes and upheavals. Figure 3 is a pictorial representation of the materials civilisation timeline, adapted from L. E. Hummel of University of Florida, USA. His book on ' Understanding Materials Science' weaves together history, properties and applications in a vivid fashion. The Fertile Crescent encompasses Sumerian, Egyptian, Mesopotomian, Babylonian and Hebrew civilisations. This covers an area, where some of the earliest use of metals occurred. The map (Figure 4) drawn by Michael Ashby of Cambridge University, UK gives a panoramic view of this development in the use of materials over ten millennia. A graphic depiction of the different classes of materials from ceramics to metallics, polymerics and more recently to composites is vividly brought out. The passage from discovery through development to design of materials can be noted. The diagram is beguiling in its chronological scale. In time scale the past fifty years occupy the same space as the preceding ten millennia!

Table 1 Timeline of the Evolution of Materials

	1,000,000 BC	Man on Earth
Stone Age		
Chalcolithic Age	8000 BC	Native Copper, Native Gold,
	6500 BC	Smelting of copper from malachite, Arsenical bronze-an accidental alloy
	4000 BC	Silver
Bronze Age	3000 BC	Tin bronze
	2900 BC	First man-made iron object in the great pyramid of Giza
	2700 BC	Meteoritic iron in Egypt
	2500 BC	Lead in Indus Valley, India/Pakistan
	1750 BC	Tin
	1500 BC	Bronze by Shang dynasty in China Chinese princess discovers silk
Iron Age		
	1200 BC	Smelting of iron by Hittites Bronze bells in China
	1000-500 BC	Wrought and quenched high-tin beta bronze vessels in South Indian megalithic and iron age sites
	1000 700 BC	Greeks and Indians quench and temper iron to improve the cutting characteristics
	750 BC	Mercury
	500 BC	Deepest old gold mine at Maski, India
	500 BC	Gold, Copper-gold, Gold–platinum alloys: Mayans, Aztecs, Incas in the Americas
	500 BC	Reference to diamond in Indian Sanskrit texts
	300 BC	Crucible steel in South India, later known as wootz

200 BC	Cast iron in China
100 BC	Development of the Silk Road
AD 400-420	Delhi Iron Pillar
AD 1200	Zinc smelting at Zawar, India
AD 1400	Blast furnace for iron making
AD 1856	Bessemer Steel

The Stone Age

The Stone Age marks the time, early in the development of human cultures, before the use of metals, when tools and weapons were made of stone. Stone Age occurred at different times in different parts of the world. In Europe, Asia, and Africa it began about two million years ago. In the most advanced parts of the Middle East and Southeast Asia it ended about 6000 BC, but it lingered until 4000 BC or later in Europe, the rest of Asia, and Africa. The Stone Age in the Americas began 30,000 years ago when human beings first arrived in the New World, and lasted in some areas till about 2500 BC. Throughout the immense time span of the Stone Age, vast changes occurred in climate and in other conditions affecting human culture. Humans themselves evolved into their modern form during the latter part of it. The Stone Age has been divided accordingly into three periods: the Paleolithic (> 10,000 BC), Mesolithic (10,000-8000 BC) and Neolithic (8000-6000 BC) eras. The Chalcolithic Age, when copper emerged as a new material and was used alongside stone, lasted from 6000 to 3000 BC, eventually giving way to the Bronze Age.

Copper

Interestingly enough it is not gold or silver but native copper, which is thought to have been the first metal used by man. By the seventh millennium BC, native copper may have been used in Turkey and Mesopotamia. It was abundantly available in large masses in the Great Lakes region of North America and used fairly extensively by the North American Indians to make weapons and implements solely by hammering and annealing so that casting and smelting was not attempted. Later discoveries at Rudna Glava in Yugoslavia have shown that copper was in use there in 4000 BC, although bronze was not made at that time.

Clear early evidence for smelting copper comes from the Middle East from the fourth to third millennium BC onwards, from parts of Israel, Jordan and Egypt. Copper oxide ores such as green malachite were smelted at temperatures of around 1200 ºC. Early copper artefacts of about the sixth millennium BC are also reported from the pre-Indus Valley sites of Baluchistan in the North Western part of the Indian subcontinent close to the Iranian border. There is fairly extensive evidence for the ancient mining of copper ores from the Khetri region of Rajasthan dating to about the 3rd-2nd millennium BC.

The Eight Metals of Antiquity

Stone Age and Bronze Age saw the early uses of the eight major metals of early antiquity: gold, silver, copper, mercury, tin, lead, zinc and iron. Copper has already been discussed under the Chalcolithic Age, which was an offshoot of the Stone Age. A brief history of five of the other metals, gold, silver, lead, mercury and zinc, is given before describing tin under Bronze Age and iron under the Iron Age. This account provides context to the development of wootz steel.

In the ancient past, the first metals to be utilised were those found in the native or elemental state, and then progressively those metals were used which could be easily extracted or smelted from their ores. The smelting of metals, which were more difficult to extract from ores, was mastered later. Most of the metals and elements indicated in the Periodic Table were in fact identified only in the last few centuries.

Gold and Silver

The noble metals, gold and silver, are found in the native state, and were used to make jewellery and sheet metal due to the great ductility and lustre of the pure metals. Some very early rich finds of gold artefacts come from the cemeteries in Bulgaria in Europe (5th millennium BC) with accoutrements of hammered and sheet gold. Most elegant gold vessels were made by the technique of repoussé in ancient Mesopotamia (ca 2500 BC). One of the most truly spectacular of ancient metal artefacts is the gold casting of the enigmatic face of the young Pharaoh Tutenkhamen (ca 1300 BC) - one of the many metal masterpieces of ancient Pharaonic Egypt (Figure 5). The gold dagger, interred with his mummy is a precious artefact.

Fine early gold and silver ornaments from the Indian subcontinent have been uncovered from Indus Valley sites (ca 2500 BC). In ancient times, gold was collected by panning alluvial sands from placer deposits. However, India has the distinction that the deepest ancient mines in the world for gold come from the Maski region of Karnataka with carbon dates from the middle of the first millennium BC. Interestingly, as far as silver production goes, the Aravalli region in north-west India along with Laurion in Greece and the Roman mines of Rio Tinto in Spain ranks amongst the few major ancient silver producing sites from about the middle of the first millennium BC onwards. The South Americans, the Mayans, Aztecs and Incas, had taken the use of gold and related alloys to some of its greatest heights.

The significance of gold in Indian antiquity is abundantly borne out by many references in Rig Veda Samhita, the Atrhasasthra and the Tamil classic, Silappadikaram. In its literature such as the legendary Ramayana, the golden deer, though it was an ilusion, was sufficient to distract Sita and provide a fateful twist to the story.

Lead

In Predynastic Egypt (ca 4000-3000 BC) galena or lead sulphide was used in the manufacture of *kohl* or eyeliner. Indeed a striking feature of Egyptian art is the beautiful and exaggerated lining of the eyes. Stone palettes for grinding kohl are found along with artefacts of lead indicating that lead was one of the earliest metals to be smelted. Lead ore is easily reduced and does not require very high temperatures. Lead has been found at sites of the Harappan civilisation (ca 2500 BC), which stretched over the North Western part of the Indian subcontinent in modern Pakistan and India. The Harappan civilisation ranks after Egypt and Mesopotamia amongst the oldest civilisations of the world. While it is can be said to fall well short of them in terms of range and wealth of material culture, it shows evidence for the most developed urban town planning. A common use for lead was to alloy it with copper and bronze for making castings. In De Re Metallica, a Renaissance period text authored by Agricola more than five centuries ago, the Westphalian process of smelting lead ore is described where lead ore is smelted in an open hearth. The mineral-rich Aravalli region of Rajasthan was one of the important early lead mining regions in antiquity.

Mercury

Mercury is a metal that has been of great alchemical importance in ancient times. In ancient China there is evidence that mercury was used by the latter half of the first millennium BC, while mercury metal is reported from Greece. Mercury is a volatile metal, which is easily produced by heating cinnabar followed by the downward distillation of mercury vapour. Some evidence for mercury distillation is reported from the ancient Roman world. Some of the earliest literary references to the use of mercury distillation come from Indian treatises such as the Arthashastra of Kautilya dating from the late first millennium BC onwards. In India, vermilion or cinnabar i.e. mercuric sulphide has had great ritual significance, typically having been used to make the red bindi or dot on the forehead of Hindu women. Mercury figured prominently in Indian alchemical texts. Ingeniously in ancient Chinese tombs cinnabar was used successfully as a preservative to keep fine silks intact. Mercury was also at the heart of many alchemical transmutation experiments in the Middle Ages in Europe, which were precursors to the development of chemistry.

Zinc

The earliest firm evidence for the production of metallic zinc comes from India. Of the eight metals used in antiquity zinc is one of the most difficult to smelt since it volatalises at about the same temperature of around 1000 ºC that is needed to smelt zinc ore. As a result, it forms as a vapour in the furnace which would immediately get reoxidised and hence lost. So there are very few references to metallic zinc in early treatises. In India there is unique evidence for the extensive and semi-industrial production of zinc at the Zawar area of Rajasthan. An ingenious method was devised of downward distillation of the zinc vapour formed after smelting zinc ore using specifically designed retorts with condensers and furnaces. The zinc vapour could be drastically cooled down to get a melt that could solidify to zinc metal. The Rasaratnakara, a text ascribed to the great Indian scientist Nagarjuna, of the early Christian era describes this method of production of zinc.

In Europe, the production of metallic zinc was virtually unknown until William Champion first established commercial zinc smelting operations in Bristol in the 1740's following which it was industrially produced. Interestingly, the method of production adopted by downward distillation bears a strong resemblance to the Zawar process. It has been pointed out that Champion's process was very likely inspired by the Zawar process which would have been made known to the British during the forays of the East India Company. This transfer of technology from the East to the West has many other examples.

Another remarkable artistic innovation by Indian metalworkers of the past was the use of zinc in making highly elegant bidri ware, an inlaid zinc alloy. This art came into vogue under the Muslim rulers of the Bidar province in the Hyderabad region from about the 14th century AD. Several impressive vessels, ewers, pitchers, vessels and huqqa bases were made of bidri ware with patterns influenced by the fine geometric and floral patterns and inlaid metal work of the Islamic world where decorative metalwork reached some its most exquisite heights, as in the metalwork of the medieval Ottoman empire.

The Bronze Age

The Bronze Age refers to the time in the development of any region, before the introduction of iron, when most tools and weapons were made of bronze. Chronologically, the term is of strictly local value, for bronze came into use, and was again replaced by iron, at different times in different parts of the world. It generally succeeded a culture's Copper Age. To some extent archaeological discoveries since 1960 have upset traditional theories concerning the origins of copper and bronze technologies. It had generally been thought that the use of bronze had originated in the Middle East. However, intriguing discoveries from Ban Chiang, Thailand, suggest that bronze technology was probably known there as early as 3600 BC.

Tin

Tin ore occurs as alluvial deposits as well as ore bodies. Tin was alloyed to copper to get harder bronze for making weapons, prior to the use of iron, in the Bronze Age cultures of the world. Tin mines have existed in Turkey dating to the third millennium BC. Regular imports of tin from Cornwall in Britain during the second millennium BC, however, made the wider use of bronze in the Middle East possible. It was eventually utilized for tools and weapons.

Bronze alloys

The first bronze to be made by man was an alloy of copper and arsenic, which was a totally accidental outcome of unintentional smelting of arsenic containing copper ores. It was in use in ancient Mesopotamia prior to the use of tin bronzes. The most famous and extraordinary examples of arsenical bronzes are the bronze bulls of the third millennium BC from Mesopotamia, where the enrichment of arsenic at the surface resulted in a shiny coating. An interesting question is whether arsenic bronze was just dirty copper or an intentionally prepared alloy. Archaeologists and historians of metallurgy have attempted to explain the gradual abandonment of arsenic bronze in favour of tin bronze in the ancient Old World by making comparisons between the mechanical properties of the two bronzes. These comparisons purported to show the superiority of copper-tin alloys over alloys of copper and arsenic, although recent studies throw fresh light. Whereas tin bronzes can be work hardened more extensively than arsenic bronzes, the far greater ductility of arsenical bronze makes it a desirable alloy for the manufacture of thin metal sheet. The widespread use of low-arsenic copper-arsenic alloys in the Americas, especially in the Andean culture area, is attributable in part to the tradition there of sheet metal production in the elaboration of three-dimensional forms. Indeed, there are indications that arsenical bronze was the first superplastic alloy ever made. The phenomenon of superplasticity also characterises wootz steel as discussed in chapter 7. Arsenical fumes were of course toxic and often led to lameness. Thus, in many cultures the metallurgist is featured as a lame person. With the discovery of tin bronze the arsenical bronze faded away – yet another example of Darwinism in materials.

The use of tin bronze to cast metal figurines goes back to the great civilisations of the Old World with one of the most celebrated early bronze casting being the famous Egyptian cat which is a hollow image. Bronze began to be used in Greece by about 3000 BC. The Bronze Age in the Middle East and the Eastern Mediterranean has been divided into three phases early, middle, and late. The early phase is characterized by increased use of the metal, from the sporadic to the common. It was the time of the Sumerian civilisation and the rise of Akkad to prominence in Mesopotamia. It also generated the spectacular treasures of Troy. Babylon reached its height of glory during the middle Bronze Age. Minoan Crete and Mycenaean Greece were major Late Bronze Age civilizations. The finely crafted Greek figurines of the first millennium BC representing the numerous gods of the Greek pantheon including Venus are well known. The Bronze Age ended there about 1200 BC, after which iron technology became common.

Amongst the earliest solid bronze figurines known in the world is the tiny well executed ‘Dancing Girl’ from Mohenjodaro from the Indus Valley ca 2500 BC**.** Although the script of the Harappan civilization remains undeciphered with several contested interpretations, there is more international consensus as articulated by Mark Kenoyer, excavator at Harappa, that it might be related to the ‘proto-Dravidian’ group of languages that bear an affinity to Tamil spoken in the extreme south of India. Indeed, it has beem suggested that the inspiration from the Mohenjodaro ‘Dancing Girl’ survives in the solid bronze icons of Hindu goddesses of the 9th-10th century Chola period from the Tanjavur area of Tamil Nadu in Southern India. Chola bronzes including the image of Nataraja, famously described as the ‘Cosmic Dance of Siva’ (Figure 6) by the celebrated art historian and philosopher Ananda Coomaraswamy rank amongst the most beautiful statuary in the world. Religion, metallurgy and a sensuous celebration of life flourished together.

The very fine Buddhist bronzes of the fabled Golden Age of the Guptas of the North Central India (3rd-5th century. AD) and the Amaravati Buddhas of South Western India (ca 1st century BC-2nd century AD) were to have a far-reaching influence on the transmission of Buddhist art to Southeast Asia and China.

In China the Bronze Age did not begin until 1800 BC. Thereafter very impressive ceremonial vessels were cast into clay moulds by the late second millennium BC to early first millennium BC. The pre-Columbian civilizations of the Americas had no bronze technology until about 1000 AD. Mirrors were made of bronze in different parts of the Old World including India. Interestingly, archaeometallurgical investigations by Sharada Srinivasan on vessels from South Indian megaliths of the Nilgiris and Adichanallur (ca 1000-500 BC) showed that they were of wrought and quenched high-tin beta bronze, ranking amongst the earliest known such artefacts.

The Iron Age

If one were to name one metal, which has the maximum impact on mankind, it is iron. Iron is still the most important metal today. Of the total global annual output of metals more than 95% is iron and steel. This is close to one billion tonnes! Iron has been described as ‘the great toiler’ by S. Venetsky who wrote the classic book ‘Tales about Metals’, a delightfully light-hearted and readable account of the history of the discovery of many metals and their present and future uses. The growth of the enterprise of agriculture would have perhaps been unimaginable without the invention of the farmer’s iron ploughshare.

Iron has both creative and destructive associations. If iron has represented the sustenance of life through agricultural implements, its destructive potency has been amply demonstrated by the weapons of war and conquest. In the words of the famous Roman scientist, Pliny the Elder, of 2000 years ago,

‘Iron mines bring man a most splendid and most harmful tool. It is by means of this tool that we cut into the ground, plant bushes, cultivate flourishing orchards and make grape vines younger every year by cutting off old vines with grapes. By this same tool we build houses, break stones and use iron for all purposes. But it is also with the help of iron that we fight and battle and rob. And we do it not only at close quarters but giving it wings we hurl it far into the distance now from embrasures now from powerful human hands, now from bows in the form of feathered darts. This, I think, is the most infamous invention of the human brain. For in order to enable death to catch up with man faster, it has given it wings and armed iron with feathers. For that the blame rests with man and not with Nature’.

Cosmic Alchemy

Iron is a metallic element with symbol Fe (atomic number 26 and atomic weight 56), which is derived from the Latin term ferrum. It is the fourth most widely distributed element forming about 5% of the earth’s crust. It is the fifth most abundant element in the universe after hydrogen, helium, nitrogen and carbon. The curiosity of the young will be ignited by this prominent place of iron in the cosmos. It is because all the elements were created by nucear fusion of hydrogen and helium atoms in the stars. The nucleus of iron is very stable, preventing further fusion to heavier elements. Thus in the first phase atoms upto iron were made. When further gravitational collapse of stars occurred, leading to a supernova, the heavier elements came into being. Carl Sagan, the astronomer, has captured the origin of elements in a dramatic fashion:

"All the elements of the earth except hydrogen and helium have been cooked by a kind of stellar alchemy billions of years ago in stars. The nitrogen in our DNA, the calcium in our teeth, the iron in our blood and the carbon in our apple pie were made in the interiors of collapsing stars. We are made of starstuff."

In many languages metallurgy is known as siderurgy or its equivalent, indicating the connection that early in history man made with metallic objects falling from the sky.

Sources of Iron

Iron is not usually found anywhere on earth as a usable metal in the solid native state, unlike metals such as gold, silver or even copper, but is generally found as iron ore. The common ores of iron are hemaetite (Fe_2O_3), magnetite ((Fe_3O_4), goethite ($HFeO_2$) and limonite ($FeO(OH)_n \cdot H_2O$). The earth's mantle is also said to consist of large amounts of iron compounds in the form of iron and magnesium silicates. Nevertheless, iron does also occur as native iron in limited areas. It is known as telluric iron and is found in basaltic rocks in small pieces. It is very restricted in use. Only in Disko Island, off the west coast of Greenland it occurs in large enough pieces to be recognized and used.

Meteoritic iron

The more common examples of metallic iron that occur on earth are in fact meteoritic in origin. Meteorites have a distinct composition ranging from about 5-20% nickel, with about 8% on an average and with little or no carbon. Corrosion makes it easy for the nickel to be leached out whereby it gets dissolved and carried away by water in the ground. This often makes it difficult to identify corroded objects of meteoritic origin.

Some exceptionally large meteorites consisting entirely of iron which are known as siderites. In 1818, the Inuit people were observed using three large siderites near Cape York in Northern Greenland. These siderites can now be found in a museum in New York and are named as Woman, weighing three tonnes, Tent weighing thirty tonnes and Dog weighing 0.4 tonnes.

Linguistic evidence suggests that the Egyptians were using meteoritic iron by the late third millennium BC. There are references to iron-from-heaven which implies meteoritic iron. The Pharaoah, Tutankhamen, had an iron sword buried with him. At that time iron was more precious than gold. Hence, when an exhibition was sent overseas from Egypt the gold dagger was sent but not the iron sword! One of the earliest known man-made iron objects apparently comes from the great pyramid of Giza. Meteoritic iron was also exploited by the North American Indians to make weapons. A meteorite that fell in Java in 1749 was used to make pattern-welded blades and had a profound effect on local metallurgy. Such blades were made by welding strips of wrought iron with meteoritic iron.

The meteorite has been etched to give rise to some of the most beautiful patterns (Figure 7). Aloys Bek von Widmanstatten was the first investigator to have studied this in 1808 and hence the patterns are named after him. It may be noted that this material has cooled at the rate of one degree Celsius per million years and this has resulted in a coarse microstructure that is visible to the naked eye. This along with studies of wootz steel led to the birth of metallography: the science of observation of microstructures.

Products of Iron Smelting: Bloomery Iron and Wrought Iron

Pure iron melts at 1536 ºC. Its melting point is reduced several hundred degrees by carbon and phosphorus content. This high temperature was hard to achieve in antiquity and hence iron was generally produced and worked in the solid state. However in China, it was produced in the liquid state as cast iron.

Bloomery iron is the first product of smelting. It is a solid, spongy mixture of iron and slag. Slag is a glassy substance that results from mineral impurities in iron ores reacting with lime or limestone added to the furnace charge. Blooms are very heterogeneous in composition with local variations of 0-2% slag, containing large voids and inclusions of unreacted minerals. Inclusions of slag, make the bloom brittle while cold, but malleable while above 250 ºC. Smithing is necessary to force out excess slag and impurities and consists of hammering and annealing at 1000 ºC, at which temperature the slag is molten. This process squeezes out molten slag, while hammering breaks up slag and distributes it in fine slag stringers. The remaining slag does not appear to have had a deleterious effect; actually it aided the welding together of internal voids. Slag also acted as a flux, spreading over the surface to prevent oxidation. Wrought iron is produced after bloomery iron has undergone a smithing process to expel the slag. Wrought iron is thus quite ‘pure’, with almost no carbon content; however some slag may still be present.

Advent of Iron Smelting

The Hittite kingdom of the mid second millennium BC was one of the major early iron producing centres and was thought to have had at one time a monopoly of iron production, following which iron seems to have become widespread in Greece and the Mediterranean by the beginning of the first millennium BC. The Hittite records (1700-1200 BC) suggest that they were aware of two different types of iron, the black one, which had fallen from the heaven and the other, which was from the earth. The former may be taken to refer to meteoritic iron, while the latter suggests that smelting of iron from ores was being practised during this period.

In the 13th century BC, the Hittite king Hattusilis III is said to have sent a letter to the Assyrian king Shelmaneser I which is remarkable for the little details it puts in which suggests that the Assyrian king had requested him for good smelted iron which he could not immediately supply due to the poor quality of ore he had just then but which he was trying to arrange for. It conveys that the Hittites were indeed smelting iron by this period:

"As for good iron about which you wrote to me, there is no good iron in my storehouse in Kizzuwatna. The iron is of too low (a grade) for smelting. I have given orders and they are (now) smelting good iron. But up till now they have not finished".

It has generally been assumed that the Hittites, who have been described as Aryan-speaking tribes, had the monopoly on iron production and that its knowledge eventually diffused from them to various places including India.

One reason why it had been believed that iron smelting may not have developed independently but may have diffused around the world from the place of its origin has been because it is a technically sophisticated process requiring high temperatures. However, such diffusion theories are perhaps not as fashionable today as they were some decades ago. There are more arguments for independent or regional development of technologies in different parts of the world including parts of India.

Iron smelting was not practised in South America until the Spanish arrived. In Africa the great Nile Valley civilisation of Egypt was the hub of the greatest advances in materials in early antiquity. The Nubian civilisation of Sudan reached great heights at the eastern tip of Africa. However, these developments do not seem to have spread down to Sub-Saharan Africa**.** This region presents an interesting picture since the origins of iron smelting there are poorly understood. Before the advent of iron production, metal production seems to have been minimal. There seems to have been no marked 'Bronze Age', so that the impact of new technology of iron smelting seems to have been dramatic and spread very rapidly. Knowledge of iron production could have diffused from Asia Minor/Middle East via Sudan/Ethiopia or from East and West Africa. However, recent exciting finds seem to suggest that iron smelting of considerable sophistication involving large furnaces evolved indigenously in the area of Lake Victoria in Africa nearly 2000 years ago. A brief reference to the different practices in iron making followed by three Asian nations, namely India, China and Japan follows.

The Beginning of the Iron Age in India

The Sanskrit word *ayas,* which occurs in the sacred Hindu scriptures of the Vedas (conventionally dated about ca 1500 BC), is very similar to the Indo-European or Indo-Germanic word for iron, eisen, from which the word iron itself derives. Iron seems to have been used in India from about the late second millennium BC. The forging of wrought iron reached its zenith in India in the first millennium AD.

Francis Buchanan and Verrier Elwin have given detailed reports on iron smelting furnaces in India in the 18th to early 20th century. A tribe, known as the Agarias specialized in iron smelting. Agaria means a person who worked with fire. The art of iron smelting was kept as a tribal secret for generations. A more detailed account of iron making by the Agarias is given in chapter 9. Concurrent with the production of iron the manufacture of crucible steel seems to have occurred in Southern India by 300 BC. This will be discussed in chapters 3 and 9.

Delhi Iron Pillar: The ‘Rustless’ Wonder

The earliest large iron forging in the world is the famous iron pillar at New Delhi dated by inscription to the Gupta period (ca AD 400) at a height of over 7 metres and a weight of about 6 tonnes. Figure 8 is a visualisation of the Emperor Chandragupta II Vikramaditya inspecting the inscriptions made in his honour. The pillar is believed to have been made by forging together a series of disc-shaped iron blooms and has been the subject of much speculation due to the fact that it has withstood significant corrosion over so many centuries.

While the reason for its corrosion resistance has been the subject of much speculation, almost as much of a mystery has been the question of how such a massive pillar was actually forged. There are differing opinions on this. T. R. Anantharaman, Ashram Atmadeep, Delhi has argued that it was forged vertically by patiently piling up pancake after pancake of bloomery iron and wrought hammering them, while R Balasubramaniam, Indian Institute of Technology, Kanpur has suggested that it was forged by propping it up in the horizontal position. Apart from the dimensions, another remarkable aspect of the Delhi iron pillar is the absence of corrosion. This has been linked to the composition, the high purity of the wrought iron, the phosphorus content and the distribution of slag. In the olden days a popular pastime of tourists to the Delhi Iron Pillar was to hug it, although more recently it has been cordoned off to protect it from the corrosive effects of sweat. There are other such well-preserved monumental iron pillars such as the one at Dhar in Central India. But remarkably, there are also such examples in humid regions more prone to corrosion such as the iron pillar at Kodachadri in coastal Karnataka, which gets a heavy monsoon. The iron beams of the Konarak temple are also in a good state of preservation despite being by the seaside, where the sea salt is known to be highly corrosive. Balasubramaniam has argued that the corrosion resistance of the Delhi iron pillar is due to the formation of a passive protective layer, which was aided by the high phosphorus content.

Cast Iron -A Chinese Invention

The production of cast iron requires higher furnace temperatures and more reducing conditions than the bloomery iron process. It was produced in China prior to other parts of the world in small blast furnaces, which were precursors to the modern blast furnaces. Cast iron with a high carbon content of between 2 and 4% is a brittle and fairly unworkable alloy with poor strength, but it has the lowest melting point in the iron-carbon system being a eutectic at 1149 ºC. By the early Christian era cast iron was used in China on a very large scale for producing tools, weapons, vessels and utensils. Figure 9 shows a massive pagoda made out of cast iron in Luoning, Shantung province of China. It was cast layer by layer in octagonal sections and is 78 feet in height.

It is impressive to note that China made cast iron as early as 200 BC. In Europe the use of cast iron was not appreciated until after about the 14th century when it was used for making cannon. By the end of the 18th century cast iron began to be used extensively in

England in building and construction, including bridges and other structures. The first metal bridge in Europe at Ironbridge over River Severn was erected in 1799 and contained 400 tons of cast iron. The famous Mysore Palace in Mysore near Bangalore built by the Wodeyars at the turn of the century was the first royal palace in India to make use of cast iron in architectural construction.

Tatara - Japanese Iron Making

Tatara iron has ben produced in Japan for about 1000 years. It was introduced from Korea in the latter half of the sixth century AD. In the Meiji era iron and steel were imported from Europe and made the Tatara process almost extinct. There is a revival of interest in the Tatara process. Even now this ancient manufacturing process is preserved in Yokota in Simane prefecture. The box type Tatara furnace is made out of clay and is approximately 3m long, 1.5m wide and 1.2 m high (Figure 10). The use of iron sand powder is characteristic of this process. It led to the production of tama-hagane (Figure 11), the Japanese term for this unique material. This was the main source for making the Japanese sword.

The Silk Route

The development of silk by the Chinese is a fascinating story, which has an indirect bearing on the history of materials. It was traded across two continents along the Silk Road/Route, spanning China, Central Asia, Northern India going back to the Parthian and Roman Empires. The Silk Road connected the Yellow River Valley to the Mediterranean Sea and linked the Chinese cities of Kansu, Sinkiang and Iran, Iraq and Syria. In an eastern move it linked Nara, the first capital of Japan to China. Silk also wended its way into India eventually reaching places like Varanasi in the Gangetic plain and Kanchipuram in southernmost India. These places became major centres for silk as seen in the present day repute of its silk sarees. This silken bond along the Silk Route brought about increased contact among diverse nations resulting in the crucial diffusion of materials and technology. Buddhism travelled along the Silk Road from India to China, Korea and Japan altering their cultures and destinies in an irreversible fashion. The tale of silk also has a bearing on that of crucible steel, as the oasis of Merv on the Silk Road in Central Asia became a significant production centre by the end of the first millennium AD.

Diamond from India

If silk is synonymous with China, diamond has a similar association with India. The word ‘diamond’ is derived from the Greek word ‘adamas’ meaning invincible. Sanskrit texts from India dating to 500 BC refer to diamond, indicating a clear knowledge of this material. In fact the famous Diamond Sutra of Gautama Buddha uses this term in an allegorical sense to indicate that these chants can cut through illusions, just as diamond cuts through other substances. Upto the eighteenth century India was the only known source for diamond. The diamond mining and trade had the patronage of the Vijayanagar, Bijapur and Golconda kingdoms. The Golconda mines, near Hyderabad, were the most famous. Marco Polo mentions the fame of diamonds under a south Indian queen, Rudramma. Jean-Baptiste Tavernier, a French merchant, travelled in South India around 1776 and in his travelogue has recorded the extraordinary commerce in diamonds. It is an astonishing coincidence that he also referred to wootz steel from the same region.

A number of individual diamonds found in India have become famous. They are noted not only their size but also for their colour, cut and history. Tavernier had described the Great Mogul diamond weighing 240 carats. It has mysteriously disappeared since. The Koh-i-Noor Diamond weighs 101.6 carats and is now part of the British crown jewels and may have been actually cut from the Great Mogul diamond. The history of diamonds is full of several such remarkable stones including the Pitt, the Orloff, the Nizam and the Hope.

Eventually diamond was found in Brazil in 1723 and in South Africa in 1867. The earliest evidence of cutting diamonds is from Venice in 1330. In the past decade Antwerp has emerged as a major centre. India has long since ceased to mine diamonds. In a remarkable comeback, Indians have emerged as major entrepreneurs in diamond cutting.

Diamond is elemental carbon, which has another form as graphite. Carbon is the fourth most abundant element in the solar system after hydrogen, helium and oxygen. Just like iron, carbon was also born out of cosmic alchemy by nucleosynthesis in the early life of our universe. While some diamonds are presolar and others have occurred during the formation of the solar system, the geodynamic evolution of the earth led to high pressures and high temperatures leading to the conversion of graphite to diamond. This extraordinary occurrence has now been duplicated in industrial laboratories to synthesise artificial diamonds.

Materials Transitions in History

The civilisational transition from the predominant use of one type of material to another raises several questions concerning the causes and factors influencing such transitions. Evidently the availability of the raw material and cost of production are primary factors. Equally important are the achievable properties. Table 2 gives the yield strength of several materials considered in this chapter. It is only one of the parameters and one must consider the combination of properties. Nevertheless some first order conclusions are possible. The superiority of alloyed bronze over metallic copper is evident. In addition, bronze has a lower melting range of 830-1100 ºC. This is less than the melting point of copper and lends itself to the production of exquisite castings. The contest between bronze and iron in terms of relative strength is interesting. While bronze has a higher strength than bloomery iron, work hardened iron has a higher value. However, it is possible to work harden bronze to reach higher values. Steel with a high percentage of carbon scores over bronze. On the other hand, iron and bronze are quite comparable in strength. Nevertheless there was a sharp transition from the bronze to the iron age. There has been speculation that this may have been due to factors of relative scarcity or decline in the supply of tin, whereas iron ores are far more abundant in the world.

In addition to purely technical reasons, such transitions are also mediated by cultural and religious traditions. Robert Ehrenreich has argued that societal beliefs led to the introduction of bronze in China. China was initially obsessed with the precious material, jade. Around 1900 BC there was a sudden explosion in the quantity and sophistication of bronze objects and in particular ritual vessels. The Chinese rulers believed that ancestral guidance was a crucial element and offerings of wine and food in large cauldrons was a part of the ritual. Bronze was needed to make these vessels. From a purely religious use, bronze then spread to making of tools and other appliances. While a belief system helped usher in a new material in China, just the opposite happened in the Andean society in South America. The Incas placed enormous emphasis on human breath and invested it with life forces. During smelting they believed that it is this life force that transmuted ore into copper metal. They did not believe that artificial aids like bellows would have the same effect. Thus they did not traverse the smelting route of other cultures and missed discovering iron.

Table 2 Material Properties as a Discriminator: Yield Strength

Pure copper	200 MPa
Bloomery iron	260 MPa
Bronze (11 wt % tin)	400 MPa
Fe-0.2% carbon	400 MPa
Work hardened iron	660 MPa
Work hardened bronze	800 MPa
Fe-1.2 % carbon	860 MPa
Work hardened steel	1600 MPa

It may also be pointed out that the reasons as to why the scientific revolution and the industrial revolutions were staged in Europe rather than in India and China, which had a dominance in these fields till 1492, are being explored by many scholars. In an intriguing essay Alan McFarlane has argued that the improvements in glass production contributed to the sweeping changes that engulfed Europe from 1200 to 1850. It led to remarkable developments in optics including the invention of telescopes and microscopes. The Islamic, Indian and Chinese civilizations did not evince the same interest in glass production and thus were left behind. This was despite fact that Islamic glass was among the most exquisite products in medieval period.

Chapter 3:

Steel and the Sword

"Everything is mine, told the gold;
Everything is mine, told the bulat.
Will buy everything, told the gold;
Will take everything, told the bulat"

-*'Gold and Bulat', Alexander Pushkin, 1827*

Understanding the Iron-Carbon Phase Diagram

An alloy refers to a combination of two or more elements of which at least one is metallic. Historically speaking, by the late 19th century European metallurgists had begun to understand and characterise binary metallic systems such as iron and carbon. They explored the various mechanisms and the types of microstructure that an alloy of two elements of a given composition can exhibit at different temperatures. The solidification from the liquid state and the transformation in the solid state were investigated. The resultant microstructures are made up of constituents known as phases. A phase diagram is essentially a graph, which shows the relationship between composition, temperature and the phases. The interest sparked by wootz steel led to the establishment of the phase diagram of iron and carbon by Sir William Roberts-Austen in 1898. This is the very first establishment of a phase diagram of an alloy. Figure 12 shows a redrawn diagram from a pioneering study by him. At that time even the principles governing phase stability were only dimly understood, as is evident from the lines in this diagram. This diagram was established without the insight provided by the Phase Rule of Willard Gibbs. Bakhuis Roozeboom of Amsterdam applied the phase rule and adjusted Roberts-Austen's disgrams in 1900. Over the next few decades this diagram came to be further refined. A historical evolution of this diagram is due to J Wadsworth (Figure 13). Special mention may be made of a study in 1868 by D. K. Tschernoff, who made important contributions to the study of wootz steel. In 1920 by Korato Honda, a pioneering steel metallurgist of Japan put the final touches to this diagram. It may be noted that the carbon composition variation leads to several families of engineering alloys: wrought iron, low carbon, high carbon and ultra high carbon steels up to 2 wt % carbon and cast irons beyond. In many other alloys based on metals such as nickel, copper, aluminium, titanium such a flexibility in composition is rarely encountered. Iron provides an embarassment of riches. It is remarkable that the metallurgists mastered the art of producing steels for nearly 2500 years without the benefit of the insights provided by these modern scientific investigations. Today steels contain not only iron and carbon but also a host of other metals. It becomes necessary to resort to higher order phase diagrams such as ternary, quaternary, quinary and so on. As the number of components increases, the diagrams become more complex. A number of phase diagrams of ternary iron alloys have been evaluated by V. Raghavan, Indian Institute of Technology, New Delhi. The first ever monograph on quaternary iron alloys is also a major contribution by him.

The binary equilibrium phase diagram is between iron and graphite. However, the industrially useful steels follow the metastable phase diagram between iron and cementite. The phases that occur are ferrite, austenite (named after Roberts-Austen) and cementite. The size, shape and interconnection among phases define the microstructure. Thermal, mechanical and thermomechanical processing provide powerful routes for the design of desired microstructures. In steels, ferrite and cementite can occur together to give rise to a eutectoidal mixture of pearlite with alternating lamellae of the constituent phases. In cast irons austenite and cementite can together form a eutectic mixture of ledeburite. Additional metastability can be introduced by rapid quenching of austenite to produce martensite (named after Adolf Martens) and bainite (named after Edgar Bain). It is this richnes in phase relations that allow the manipulation of microstrucure of steels to tune their properties. No other binary combination of elements rivals this extravagant choice offered by iron and carbon.

To comprehend the nature of wootz steel and the resultant wavy patterns of Damascus blades, it is interesting to understand how the two phases of the iron-carbon system that contributed to its alternating light and dark etched patterns, came to be characterised historically. In 1885 Osmond called the iron-carbide thus formed ‘ciment’, which is French for binder or cement. Pearlite gets its name from the pearl-like lustre and iridescence of its appearance. When the term, pearlite, first came into vogue is not known. Recent research may provide an explanation why this particular structure is pearl-like in appearance. The regular spaced lamellae of optically quite different materials form a kind of ‘photonic crystal’ with optical properties quite different from those of the constituents. Real pearls get their lustre from the same mechanism. The name ‘pearlite’ thus is more fitting than its inventor could have known.

Figure 14 shows microstructures of steels with different amounts of carbon. Figure 14 a shows ferrite in hypoeutectoid steel with very low carbon. Figure 14 b shows pearlite in a eutectoid steel, while figure 14 c shows grain boundary cementite and pearlite in a hypereutctoid steel.

Fast cooling results in the formation of martensite (Figure 14 d). The fast cooling rate prevents the excess carbon from precipitating in the form of cementite. Instead the iron atoms rearrange to form a crystal structure that is able to trap the carbon. This is an example of diffusionless solid-state transformation, which is temperature dependent. The carbon trapped this way prevents the movement of dislocations and the crystal is thus very hard. Martensite begins to form below 220º C. Martensite can be very brittle so that tempering is used to soften it. During tempering, the steel is heated to about 220-450º C. At these temperatures some of the carbon will be able to leave the martensitic crystal structure and precipitate as carbides, leaving behind regions of pure alpha iron. This results in a more ductile structure.

Sometime in the past it would have been noticed that wrought iron could be hardened if it was heated in charcoal fire for a sufficiently long time and then cooled in water or quenched. This would have allowed some carbon to get into the iron to give low carbon steel, while the quenching would result in martensitic transformations with improved properties and hardness and this was how the edges of iron tools or weapons were hardened. Steel has several improved properties over iron of strength, ductility, toughness, hardness, cutting edge and corrosion resistance.

Introducing the Age of Steel

It is convenient to distinguish two stages in the development of steel. In this book the true Age of Steel is defined as beginning with the crucible steel process, which resulted in more homogenous true steel. It is likely that the age of steel using crucible processes began in India by the pre-Christian era leading to the wootz process. Thus the period spanning 300 BC to AD 1856 is termed as the First Age of Steel, whereby crucible steel making and cementation were two significant processes available for the production of steel. However, as the quantities produced were in kilogram size cakes applications were limited to small tools, cutlery and weapons such as swords. Iron continued during this period as the dominant engineering material. The modern Age of Steel begins with the discovery of the pneumatic process for making steel by Sir Henry Bessemer in 1856. This was to lead to a complete reversal of fortunes between iron and steel, as steel emerged as the more important material used in tonnage quantities. Till the middle of the nineteenth century steel was expensive and structural components were made of wrought iron or cast iron at the two ends of the iron-cementite phase space.

First Age of Steel

Initially, steel had to be produced separately from smelting. The first method is to add carbon to wrought iron described as a cementation process or carburisation. The second method known as decarburisation is to remove carbon from cast iron.

Cementation, case hardening and forge hardening are several terms in use to describe essentially similar processes. Wrought iron produced by the bloomery process could be carburised by heating it in charcoal for a long time. Typically this lasted several days, resulting in the solid state absorption or dissolution of carbon into the wrought iron. This process is very slow because it is a reaction in the solid state. Pieces or sheets of wrought iron were packed with charcoal or other organic materials into a closed refractory container and heated between 1050-1100ºC from five to seven days. This process could result in the incorporation of varying degrees of carbon between 0.6 and 2%. It would have resulted in a heterogeneous steel of intermediate composition. Such diffusion is less likely to have resulted in a homogenous steel of higher carbon content. The steel thus produced could have been evened out by hammering, annealing, and folding the steel many times over. There was always a significant decrease in the carbon content away from the exposed surfaces. The stringers from the slag remained in the final steel causing brittleness.

Decarburisation dilutes the carbon content of cast iron. This can involve the mixing of wrought iron with molten cast iron. In China, the heating of bundles of cast and wrought iron together followed by forging and heating led to complete diffusion and homogenisation. This would result in the partial melting of cast iron. Some carbon would diffuse into wrought iron that was repeatedly forged and heated again. The finery process breaks cast iron into small lumps, followed by heating to high temperartures in an oxidising air blast. The iron melts and carbon burns out as carbon dioxide and the decarburised iron droplets sink to form a bloom below the hot zone.

Crucible Steel Making: A South Indian Forte

It is generally believed that the original crucible steel making technique was developed primarily in India leading to wootz steel. The use of iron was well established in south Indian megalithic cultures by at least about 1100 BC at sites such as Hallur in Karnataka. Its significance for the evolution of the South Indian process of wootz crucible steel is explored further in chapter 9. The South Indian megalithic and Iron Age cultures are characterised by the fact that there is a fair deal of uniformity in the material culture over a fairly large region stretching from Adichanallur in the southernmost tip of the peninsula to the Vidarbha region just below the Vindhyas. Furthermore, the process of wootz crucible steel making seems to have been one which was so much more associated with the South Indian part of the subcontinent including Sri Lanka and was not really well known from the Northern Indian context. The megalithic site of Kodumanal, ca 300 BC, in Tamil Nadu may have been a site for ferrous crucible processing. There is a preliminary identification of a sample of high carbon steel of the composition of wootz of around 1.5% carbon from megalithic Andhra Pradesh. These are tentatively the earliest known identifications for high-carbon crucible steel in the world.

With Benjamin Huntsman redeveloping the process of crucible steel manufacture in 1740 to make cast steel bars, Sheffield in England acquired an international reputation for steel making. In fact from the 14th century onwards Sheffield was renowned for the manufacture of quality knives. In the Canterbury tales of Geoffrey Chaucer the miller carried a Sheffield knife. Within 100 years, Sheffield was producing 20,000 tons of crucible steel per year, which provided 40% of European steel production at this time. Grand as this scale is, it may be compared with accounts that in the 1600’s individual shipments of Indian wootz crucible steel ingots from Golconda to Persia consisted of up to 20,000 pounds of steel!

It remains a matter for speculation wheter Huntsman knew about the Indian crucible steel making. In an authoritative book on Steel Making before Bessemer (1984) K. C. Barraclough describes the history of the crucible steel process in Britain but makes no mention of the Indian process. P. T. Craddock, the British Museum, London has observed that there is circumstantial evidence for a number of transfers of technology including crucible steel making at the dawn of the European Industrial Revolution.

Modern Steel Age

An industrial scale steel making technology was invented in 1856 in London by Sir Henry Bessemer (Figure 15). In October 1855, Bessemer the son of an engineer took out a patent for his process of rendering cast iron into a malleable steel by the introduction of air into the liquid metal to remove carbon**.** The molten cast iron was contained in a huge tank and when hot air was blown through it, the oxygen reacted violently with the carbon to be liberated as carbon dioxide gas, thus lowering the carbon content of cast iron. British metallurgist Robert Mushet is believed to have improved on Henry Bessemer's process through a more effective de-oxidation process and also discovered the role of manganese in steel making. The pre-eminence of Sheffield was such that Bessemer moved his company to Sheffield to be at the heart of the industry.

Table 3 gives the timeline of important milestones in Indian iron and steel industry. Seveal phases can be discerned. After initiating the Steel Age in 300 BC Indian steel reigned supreme until a few centuries ago. Colonisation by the British led to the near extinction of the Indian industrial sector. In the twilight years of the nineteenth century J. N. Tata conceived of a new start to the steel industry in a bold and ambitious fashion. His effforts led to the setting up of Tata Steel plant in 1907. Another visionary Sir M. Visvesvaraya started the Mysore Iron works in 1918 at Bhadravati. This area is close to the original sites of wootz production. After India attained independence in 1947, Prime Minister Jawaharlal Nehru played a stellar role in establishing several steel plants in the Government Sector. These plants were termed by him as the modern temples of India. In the final decade of the twentieth century economic liberalisation was set in motion, making steel once more accessible to the private sector. Prior to this Lakshmi Narain Mittal decided to produce steel in Indonesia and other foreign climes and has emerged as a major steel industrialist. The twenty first century has seen many new initatives, including the acquisition of steel plants abroad by Tata Steel. It appears to presage another golden age for Indian steel.

For 2004, the global production of steel is forecast to exceed one billion tonnes for the first time in history. This gives an indication of the continued and crucial importance of steel in the modern age. In 2003, China became the first nation to produce more than 200 million metric tonnes of steel per annum, reflecting its rapidly growing economy and infrastructural expansion. In that same year India ranked eighth amongst the world's producers of steel with 31.8 million metric tonnes of steel.

Steel Processing

After the forging of swords at high temperatures, an important step in hardening blades lies in their being quenched. This step is important because it enables a martensitic transformation to take place in the steel, which contributes to improved toughness and strength.

One of the methods that Indian blacksmiths seem to have used for quenching, is to plunge the red hot blade into the tree trunk of a banana or plantain tree, one of the most universal of Indian trees which is full of sap, which was followed by cooling it overnight. Bhanu Prakash, Banaras Hindu University, Varanasi was successful in getting some of his students to produce a small blade by forge welding high carbon steel to low carbon steel. This blade was then quenched by thrusting the red hot steel blade into the green trunk of a banana tree. This resulted in some amount of tempering and greater hardening of the edge of the blade as compared to its back portion. Interestingly, in Indian antiquity, the well known scientist Varahamihira is said to have advocated a hardening and quenching treatment by plunging the red-hot sword into a solution of plantain ashes.

Some gruesome methods of quenching steel are also known. The Tamil Sangam text, Tolkapiyam, dating to the pre-Christian era, is thought to mention the quenching of a sword in a slave's stomach. It is interesting that many of the Damascus blades made in Syria from wootz steel are said to have been similarly quenched. Another method used in Syria was to run at a fast gallop on a horse holding the red hot sword with the sharp edge in the front. In this way the sword blade got rapidly air quenched.

Table 3 Timeline of Iron and Steel in Indian History

1100 BC	Iron from megalithic sites such as Hallur in Karnataka
326 BC	King Porus presented Alexander 30 lbs of Indian iron
300 BC	Crucible processes at Kodumanal, Tamil Nadu related to steel
300 BC	Kautilya showed knowledge of minerals, including iron ores, and the art of extracting metals in 'Arthashastra'.
100 BC	Roman accounts of Seric iron pointing to Chera region of South India
AD 320	A 16 meter iron pillar erected at Dhar
AD 400-420	Gupta Iron pillar (later moved to Delhi)
12th century AD	Export of iron and steel from Malabar by Jewish merchants
13th century AD	Iron beams used in the construction of the Sun temple Konarak, Orissa
17th century AD	Tavernier's accounts of export of 20,000 pounds of wootz steel from Golconda in Andhra Pradesh to Persia Manufacture of cannon and firearms
AD 1830	Suspension bridge built over the Beas at Saugor with iron from Tendulkhema (MP); J. M. Heath built iron smelter at Porto Novo, Madras Presidency
AD 1870	Bengal Iron Works established at Kulti
AD 1907	Tata Iron & Steel Company formed
AD 1914	Howrah Bridge in Calcutta built from 80,000 tonnes of Tata Steel
AD 1918	Mysore Iron Works at Bhadravati
AD 1954	Hindustan Steel Limited formed to construct three integrated steel plants at Rourkela, Durgapur and Bhilai
AD 1960	Alloy Steels Plant installed at Durgapur
AD 1972	Steel plant at Bokaro
AD 1978	Steel Authority of India Limited formed
AD 1990	Visakhapatnam Steel Plant set up Liberalization of Indian economy and the construction of private sector steel plants
AD 2004	Acquisition of overseas steel plants by Tata Steel

Swordsmanship

In order to appreciate the central role played by the Damascus sword and its variants, a brief digression on swords will be instructive. The great repute of wootz steel and Damascus steel derives in no small measure from its being a destructive weapon par excellence. Although iron by itself was harder than materials such as copper or bronze, steel has improved properties over iron in terms of hardness, ductility, cutting edge and corrosion resistance making it a superior metal for weaponry.

Types of Swords and Legendary Swords

A sword is a bladed weapon, consisting in its most fundamental design of a blade and a handle. The blade is usually of some metal ground down to at least one sharp edge and often has a pointed tip for thrusting. The handle, called the hilt, has been made of many materials ranging from jade to bejewelled cast metal, but the material most commonly used may be wood covered by leather, fish skin or metal wiring. The parts of a sword and the basic intent of swordsmanship are remarkably consistent between cultures.

Essentially swords have been in use right from the Bronze Age when the construction of long metal blades was possible for the first time. Early swords were made of solid bronze or copper, which were however not as hard as ferrous implements, while bronze could also be brittle. Not until iron could be forged did the sword truly become an important weapon. Soon, smiths learned that with a proper amount of charcoal in the iron, a harder metal could be produced. This was nothing but steel.

There are several hundred types of swords. The rapier is a longer European dueling sword, optimised more for thrusting than a slashing action (Figure 16). Amongst the well known Japanese Samurai swords rank the Katan, Tachi and Wakirzashi. Claymore refers to types of Scottish swords. A sabre is a sword with curved edge intended for slashing or chopping. Jian is a Chinese double-edged thin straight sword. Dao is a Chinese single-edged broad curved sword. The Damascus blades were known for the ‘jauhar’ or wavy pattern that they exhibited. Some of the well-known blades included the Persian shamshir, which was curved for the drawcut and the Indian talwar. Other types of Indian swords include the katar or katti also used in the Deccan.

Many swords in mythology, literature and history are named after their wielders or the swordsmiths who made them. Some of these have also come to gain a metaphorical significance such as the ‘Sword of Damocles’, which implies a loomimg threat hanging over one’s head. Some of the more celebrated ones are King Arthur’s Excalibur, Kusanagi (Grass-cutter) - the Japanese equivalent to Excalibur, Roland’s Durendal, Sword of Damocles and El-Cid’s Tizona.

An Explosive Transition in Weaponry: Gunpowder, Cannon and Guns

The sword made of steel marked an important development in weaponry, replacing wood and stone weapons of varying shapes. It was influential in deciding the course of history for more than a millennium, as nations fought each other. However, the inexorable process of evolution in weapons in the form of gunpowder, cannon and guns ended the supremacy of swords. Nevertheless, such is its strong hold on the human imagination that it continues to be used for ceremonial purpose by the military even today.

Gunpowder is believed to have originated in China in the ninth century. Two possible motivations are ascribed for this discovery. One was an accidental event by the Chinese alchemists seeking the elixir of immortality. The other was to frighten evil spirits by the loud noise created by this. Gunpowder is a mixture of sulphur, charcoal and saltpeter (potassium nitrate). Since saltpeter is not naturally occurring, its discovery signifies a deliberate investigation. Its use in pyrotechnical fireworks is well known. In the tenth century gunpowder was used in China for military objectives in the form of rockets and bombs fired from catapults.

Through the Silk Road the art of making gunpowder spread to Arab countries. During the 11th Century crusades Europe became aware of gunpowder. In Europe it led to the creation of the cannon. The English used them in some famous battles: Crecy (1346), Poitiers(1356) and Agincourt (1415). Further development from the 15th to the 17th century thoroughly changed the nature of the warfare. Powerful cannon could destroy the walls of medieval castles and forts and guns replaced bows and swords, effectively ending the Middle Ages. The remarkable developments were carried back to China by Jesuit missionaries during the late Ming and early Qing emperors. There was an evolution in the materials used in the manufacture of cannon. The early ones were made of wooden staves reinforced with metal straps. This was followed in quick succession by wrought iron, cast iron and bronze.

Further advancement in metallurgy led to the development of small weapons such as muskets and guns. Germany developed a mechanical means of igniting the gunpowder around 1411. The development of smokeless powder with gelatinized nitrocellulose leading to the discovery of cordite by Alfred Nobel in 1887 and gave birth to modern automatic firearms. This evolution may be likened to the impact that Bessemer had on steel making.

Medieval India manufactured many cannon. These are found at Nurwar, Mushirabad, Bishnupur, Bijapur, Gulbarga and Thanjavur. The 17th century forge-welded iron cannon at Thanjavur has been studied in detail by Balasubramaniam and his colleagues. The technique of manufacture is akin to that employed in the Delhi and Dhar iron pillars.

A recent book “Gunpowder: Alchemy, Bombards and Pyrotechnics” by Jack Kelly traces these developments in a fascinating narrative and sketches an eclectic cast of characters, including Michaelangelo, Edward III, Vasco de Gama, Cortez, Alfred Nobel and E. I. Du Pont.

Chapter 4:

The Romance of Wootz Steel and the Damascus Sword

"There will never be another nation,
which understood separate types of swords
and their names, than the inhabitants of India…"

-Al-Biruni (973-1048 AD)

A Matter of Definitions

The etymology of wootz and Damascus sword is intriguing. The term for Indian steel, wootz, is an anglicization of the word 'ukku' which was the word for crucible steel encountered by European travellers in the Kannada speaking region of Karnataka and Telegu speaking region of Andhra Pradesh. The term 'ukku' may have a hoary ancestry traceable from India's oldest living classical language, Tamil, so designated because it has been continually spoken and written relatively unchanged for some 2500 years. For example, the word 'ekku' steel in Old Sangam Tamil of that era, while 'urku' even in modern Tamil suggests the oozing of liquid reminiscent of a crucible process. The term 'wootz', itself appeared for the first time in 1795 in George Pearson's lecture on Indian steel to the Royal Society. The wootz ingots were produced in Southern and South Central India and Sri Lanka. The area of Hyberabad, formerly Golconda, was perhaps the most reputed area of the production of wootz.

Another term that is common in this context is the 'pulad' of Central Asia. The oasis of Merv where crucible steel was also made by the medieval period lies in this region. The term 'pulad' appears in Avesta, the holy book of Zorastrianism and in a Manichéen text of Chinese Turkestan. There are many variations of this term ranging from the Persian 'polad', the Mongolian 'bolat' and 'tchechene', the Russian 'bulat', the Ukrainian and Armenian 'potovat', Turkish and Arab 'fulad', 'farlad' in Urdu and 'phaulad' in Hindi. It is this bewildering variety of descriptions that was used in the past that makes a study of this subject so challenging.

The word 'damask' has also several interpretations. A look into the dictionary indicates that 'damask' has many colourful and varied associations. The most predominant of these ascribes the term to the city of Damascus, as indeed, Al-Kindi refers to swords made in the city of Damascus. A second major meaning has nothing to do with the geography but refers to the pattern. Damas in the Arabic language means water. Hence the watered pattern seen on the sword led to its being termed as Damascene swords. The word also relates to textile texture, whereby Damask silk refers to silk woven with an elaborate pattern of flowers and the like. In other shades of meaning, 'Damask Rose' has a deep rose colour and the Damask plum, is a small dark-coloured plum, generally called damson. The popularity of the word is reflected in its many versions in different languages. There is Damascus in Latin, Damaskos in Greek, Dammesq in Hebrew, Daemeshq in Arabic, Damasco in Italian and Spanish, and Damas in French. In another interesting turn of phrase, in modern times the name has been applied to patterns in integrated circuits with copper interconnects.

It is useful to distinguish between the two separate metallurgical categories of ‘true’ Damascus steel and swords and the mechanically formed Damascus swords. The former is essentially made from an ingot of high carbon steel, i.e. wootz, with a texture originating from the etched crystalline structure. It is incredible but true that a similar pattern can be produced by an altogether different process. This second variety is essentially a composite structure made by alternately welding together low carbon iron and higher carbon steel to give a visible pattern of dark and light wavy bonds on the surface on the surface.

Timeline of Wootz Steel and the Damascus Sword

Timelines are extremely convenient guides for following the interwoven story of wootz steel and the Damascus sword. As it indicates, interest in these two objects has been sustained over two millennia and continues to this day. It is possible to divide these into three convenient periods, which will be the subject of the following chapters. The first period covers the years from 300 BC to AD 1500, when essentially historical or literary accounts including poems and myths are the main sources. The second period covers the period from the 16th to the early 20th century when the Europeans came to India originally as traders but stayed on to explore colonial designs leading to British colonization. The European travellers in India left their vivid accounts of the legacy of wootz steel making still being practised. The 17th to early 20th centuries marked an excitement in Europe. In trying to unravel the secrets of wootz steel European metallurgists laid the modern foundations of materials science. The third period covers the latter half of the twentieth century, when several groups especially in the USA, added to modern metallurgical knowledge concerning this ancient steel. A chronological account makes for a surprisingly coherent evolution as indicated in Table 4 and Table 5.

Table 4 Timeline – Wootz Steel and Related Items (300 BC- AD 1500)

300 BC	Preliminary finds of crucibles and high-carbon specimens from south Indian megalithic and Iron Age horizons. Possible production of semi-solid/molten steel by crucible method for the first time in history
323 BC	King Porus gifts *ferrum candidum* or ‘bright iron’ to Alexander the Great
100 BC	Fire-welding technique to produce iron weapons with a steel cutting edge developed in Europe
AD 100	Advent of pattern-welded steel with twist and chevron patterns in Europe
AD 300	Alexandrian alchemist, Zosimos of Panopolis, publishes an unequivocal reference to Indian crucible steel
AD 500	Merovingiens and Carolingiens in Europe use pattern-welded steels
AD 800	Vikings use pattern-welded steels
AD 900	Crucible steel production spreads to Merv in central Asia

AD 900-1000	Pattern-welded swords known as the Kris are made in Indonesia
AD 1095-1270	Europeans are overawed by the superior Damascus Sword during the Crusades
AD 1100	Saladin, the Saracen warrior from Egypt, demonstrates the Damascus sword of wootz steel to Richard the Lion hearted, King of England
AD 1400	Pattern-welded steel is not used any more
AD 1500	Blacksmiths of Russia produce 'bulat' steel

Table 5 Timeline – Studies on Wootz and Related Items (16th –21st century)

1589	Giambattista della Porta of Italy emphasises heat treatment of wootz steel- the first recorded scientific enquiry?
1677	In a first enquiry in the UK, Joseph Moxon sets temperature limits for forging South Indian wootz steel
1722	Reaumur mentions that Indian steel could not be forged by Parisians
1784	Tobern Bergman, Sweden, links difference between iron and steel to carbon
1795	The first scientific lecture by Mushet of England on the wootz steel George Pearson presents his work on wootz steel to Royal Society
1820	Michael Faraday and James Stodart erroneously attribute the quality of wootz steel to silica and alumina
1824	J. R. Breant in France studies hypereutectoid steel in the context of wootz steel
1827	Alexander Pushkin published his poem, 'Gold and Bulat'
1837	Henry Wilkinson, sword manufacturer, examines patterns in wootz steel
1841	P. A. Anasoff of Russia reproduces wootz steel
1868	D. K. Tschernoff reproduces Breant's experiments
1918	Nicolai T. Belaiew, Russian scientist, works on wootz steel in the UK
1960	Cyril Stanley Smith highlights the importance of wootz in antiquity
1985	Oleg Sherby and Jeffrey Wadsworth connect superplastic ultra-high carbon steels with the steel used for Damascus swords
1990	Thelma Lowe finds wootz crucibles from Konasamudram in southern India to be a high-performance refractory
1994	Manfred Sachse, German sword smith, recreates Damascus patterns Sharada Srinivasan discovers production sites for wootz at Mel-siruvalur, Tintini and Machnur and studies crucibles from megalithic Kodumanal
1996	Gillian Juleff's experimental re-construction of wind blown iron smelting furnaces from Sri Lanka
1998	J. D. Verhoeven and Alfred Pendray identify vanadium as an important element in creating the Damascus pattern
2002	Ann Feuerbach demonstrates that crucible steel was produced in Merv in Central Asia in AD 900

	Ric Fuller demonstrates the art of making of Damascus blades at the Smithsonian Folklife Festival during Silk Road exhibition in Washington
2003	Greg Olson uses quantum mechanics to design Dragonslayer sword

Indians as Master Steelmakers and Swordsmiths

There is a plethora of historical accounts from around the world, which conjure up the picturesque and fanciful images of the fame that Indian iron and steel seems to have enjoyed. When many consider that a scientific temper has not yet been deeply inculcated in modern India, where many people's lives are still guided by superstition, it comes as a pleasant surprise to note the high esteem in which some of the skills of Indian metallurgists and metal workers were held. It bears testimony of the existence of a technological temper and a sense of experimentation in Indian antiquity. It is useful to keep sight of this in order to make more positive assessments of our past achievements and to shed the negative self-image that stems from our colonial legacy and Eurocentricism. At the same time, it is also important to take a balanced view of our heritage rather than indulging in chauvinistic glorification of our past. One must bear in mind that it is not just India, but several cultures, including non-western cultures around the world, have made several interesting innovations.

Some the earliest evidence suggesting that Indian iron was coveted abroad comes from the Mediterranean region in classical Greek and Roman accounts of the latter part of the first millennium BC to the early centuries AD. Admiring accounts of Indian iron are also found in early medieval Arabic and Persian accounts. Such accounts of 'iron from the Seres' and 'Teling swords' and some preliminary archaeological evidence seems to locate such a skilled steel making tradition in parts of Southern India. Significantly, there are eye-witness accounts and traveller's tales of the making of wootz steel in many parts of Southern India. Indian wootz ingots are believed to have been used to forge oriental Damascus swords, which were encountered first by the Europeans during the Crusades of the 12th-13th century AD. They were then reputed to cut even gauze kerchiefs.

It has generally been believed that the best of the Damascus blades were made outside India, albeit from Indian steel, in places such as in Persia and Damascus. This is exemplified by some of the fine swords found around the Islamic world from the 13th century onwards, including Turkey, Central Asia and Islamised India. However, Al-Biruni's mid 9th-11th century accounts suggest that prior to this period it was swordsmithy and steel from the Indian subcontinent, which was the most superlative. This bears testimony to the high scientific and technological traditions of pre-Islamic India, of Hindu-Buddhist civilisational affiliations. As with the case of 'Arabic numerals', which reached the West through the Arab world but were essentially based on of the decimal system and zero of Indian origin, the previously unparalleled Indian traditions of steel and sword making became known to Europe through the Islamic world. The high technologies of Indian steel making were then taken to unsurpassed heights of artistic, technical and decorative sophistication in the Islamised world from where several artefacts of crucible steel are known, often being elaborately inlaid, gilded or bejewelled.

Although the knowledge of making Damascus blades is reported by some to have disappeared in the Middle East by the 14th century, this cannot be true of other parts of the world as there are watered steel blades found in Indian armoury of the 16th- 19th century.

The glowing accounts of Indian proficiency in sword and steelmaking over the ages continue to astonish even today. This is because India has over the centuries acquired a reputation of being a non-violent nation, having nurtured an admirable list of great figures, who propagated the path of ahimsa or non-violence. Whereas in much of the world, it has been power, military conquests and victory in battle that have been glorified, India's history blazed a new trail by glorifying the renunciation of power, violence and conquest through warfare. Such towering figures include Buddha, who renounced his princely life as Siddhartha, and Mahavira, founders of the agnostic, heterodox faiths of Buddhism and Jainism respectively. The Indian emperor Asoka, ca 3rd century BC was sufficiently moved after his bloody victory in the battle of Kalinga to renounce warfare and embrace the path of Buddhism and ahimsa. Asoka was responsible for the spread of Buddhism far and wide. Eventually Buddhism reached China, Korea and Japan and became a world religion. A more recent Indian icon of world renown has been Mahatma Gandhi who led India's non-violent freedom struggle against British colonial powers and became known as the 'Father of the Indian Nation'.

Apart from the accounts of Al-Biruni and Edrisi, the accounts and sketches of Indian armoury made by the Lord Egerton of Tatton in his book of 1896 'A description of Indian and Oriental Armour' also point to the quality and sheer diversity of ancient Indian armoury ranging from courtly to tribal traditions. That relatively so little has indeed survived of Indian armoury may be explained by factors such as the historical upheavals of war and conquest. The destruction of heritage can also be attributed to periods of Islamic and Portuguese rule and the treasure hunting of the Dutch, the French and the British. For example, as mentioned by Egerton, sweeping disarmament drives were undertaken by the victorious British after various wars such as after the Indian sepoy mutiny of 1857 when scores of Indian weapons were destroyed and several stores of armouries were dismantled. Another reason why so little may survive of our metalworking heritage may be because Indians, at least since the historical period, did not have a burial tradition unlike many other cultures in the world. In China and Egypt artefacts were enclosed in burial chambers and jave been preserved over several centuries. Besides, relatively little is known about ferrous artefacts in non-weapon applications such as implements and tools for agriculture, handicrafts and musical instruments.

Tales from the Mediterranean: Iron from the Seres

An array of lively accounts from a range of sources in antiquity, especially from the Mediterranean and the Middle East, testify to the high repute and demand for ferrous metals from the Indian subcontinent. These have been summarised by various scholars. Special mention must be made of Bennet Bronson, who wrote in 1986 a seminal article entitled the 'Making and Selling of Wootz'. Amongst the early accounts related to the use of iron in ancient India may be one attributed to the Greek historian, Herodotus, who wrote about the battle at Thermopylae (ca 480 BC). It has been said that Indians were part of the Persian army in this battle and they are said to have used cane arrows with iron tips.

Perhaps the most oft-repeated story comes from the time of Alexander the Great, the Greek king of Macedonia. Alexander's ambitions of world conquest brought him from across the Mediterranean to the North Western tip of the Indian subcontinent in 327 BC. The story goes that Quintus Curtius who lived in the first century AD wrote that during the campaign of Alexander in the Indus region he was presented with a hundred talents of *ferrum candidum*, or "bright iron" from India. However, according to some accounts, this *ferrrum candidum* was presented to Alexander after he defeated the Indian king Porus in battle. Porus is said to have been the ruler of Takshashila, then a great Buddhist centre, i.e. present day Taxila in Pakistan, and is believed to have been a just and gracious king: the epitome of dignity in defeat.

Egerton gives a vivid description, which conveys the drama of the historic battle between Alexander and Porus in his book, 'A Description of Indian and Oriental Armour':

"From the accounts of Quintus Curtius we learn something of the character and condition of Indian armies at that period, how gallant was their defence but how little able they were to oppose the superior tactics of the Greeks. Alexander crossed the Jhelum by a strategem, taking advantage of the cover offered by a wooded island. The opposing force of Porus consisted of 85 elephants, 300 chariots, each of which carried six men, two bearing shields, two archers, and two driving the horses and throwing darts; 30,000 foot, among whom were archers who shot barbed arrows difficult to extract, and 4000 horse. Alexander's first onset was with the chariots, which got into confusion from the slippery nature of the ground, and lost their drivers, after inflicting some damage on the Macedonian infantry by the vigour of their charge. The elephants formed the second line, and behind them were the infantry, and the archers who beat drums during the fight…"

Although it is generally believed that the gift of bright iron was made to Alexander by Porus, Bronson points to other evidence that the 100 talents were in fact presented by the vanquished chieftains or tribesmen, Malloi and Oxydrakai. Of course, these 'hundred talents', which sound like a most grandiose figure, come to a more modest amount of about three tons in all. One can only picture the sight of these hundred talents being presented as indicated along with a whole cavalcade, of an assortment of horses, chariots, fine cloths and textiles for which India has been famed. Bronson cautions that there is no basis for concluding that this gift consisted of steel rather than iron. However, one reason why it has often been thought to be a gift of an exotic material like steel rather than iron may be because iron may have been too commonplace to have made such a significant gift which has been part of folklore for so many centuries. Figure 17 imaginatively captures this encounter-where the twain of East and West may have met through wootz steel with a touch of pathos conveyed by the playing of the harp!

Another well-known account comes from Roman sources of the first century BC to the first century AD such as by the elder Pliny in his work ‘Natural History’, the encyclopaedia of the Roman Empire. Pliny prominently mentions the import of iron from the ‘Seres’, which may be identified with the South Indian Chera region. It is perfectly reasonable to identify the ‘Seres’ with the ancient Tamil Cheras of the south of India when we consider that the classic Tamil Sangam literature refers to the Cheras as one of the ruling dynasties of this time probably in the region of South Western Tamil Nadu. Furthermore, Sangam literature also gives lucid accounts of the brisk trade with the ‘Yavanas’, while archaeological excavations at sites such as Arikemedu confirm that the Romans were trading at ports in southern India at this time.

The Periplus of the Erythreaen Sea, a well-known Roman travelogue by an anonymous sailor, also mentions the kingdom of the Seres/Cheras and especially their port Muziri, which was an active shipping centre on the western coast of India. Muziri is identified with the Malabar Coast of Kerala. In this context, it may be noted that at least from the medieval period onwards, the Chera region has been associated most closely with the Malabar Coast. The accounts of iron from the Seres would then particularly make sense if the accounts were referring to the ferrous metals being exported from ports on the Malabar coast across the Arabian sea to the Mediterranean although they could well have been produced in inland Southern India in the regions where iron ores abound, such as the Salem region of Tamil Nadu and parts of Karnataka or even Andhra Pradesh. The fact that ‘Seric iron’ was in demand as an item of import in the Roman world could imply that it referred to something special like wootz crucible steel rather than ordinary iron. T. A. Richard, who wrote a paper in 1939 on primitive iron smelting in the American Journal of Archaeology commented about wootz steel that:

‘..It was not made by the Arabs at Damascus but by the Chera Tamils in Hyderabad, where it obtained the name, wootz, under which it was exported from India shortly before the Christian era.’

An account of the Alexandrian alchemist, Zosimos of the third century AD also suggests the use of crucible processes in India. P. T. Craddock has pointed out that the chapter on ‘The Tempering of Indian Iron’ by Zosimos contains unequivocal reference to crucible steel. A short description shows that soft iron was to be broken into small pieces, mixed with fruits of the palm tree and magnesia and placed in a crucible. Then charcoal was put on it and the fire was blown until the iron became molten and the components became united with it. This is indeed clear affirmation that the first molten steel was an Indian invention. Bertholet in his monumental ‘Collections des Anciens Alchemistes Grecs’, published in 1893 included a translation of the papers of Zosimos.

‘Hinduwani’ or Indian steel: Arab and West Asian Accounts

One is indebted to Arab sources for providing some of the most historically significant accounts which may point to the primacy of Indian iron and steel in ancient times. Aus Hajr, an Arab poet, wrote in admiration in AD 540 that:

“It has a water whose wavy streaks are glistening. It is like a pond over whose surface the wind is gliding. The smith has worked out in a grain as if it were the trail of small black ants that had trekked over it while it was still soft.”

Edrizi mentioned that the Indians had workshops where the most famous sabres in the world were forged. The 12th century writings of Edrizi are translated and quoted by Henry Yule in ‘The Book of Ser Marcopolo the Venetian Concerning the Kingdoms and Travels of the East’ as indicated below:

‘*The Hindus excel in the manufacture of iron, and in the preparations of those ingredients along with which it is fused to obtain that kind of soft iron which is usually styled Indian steel (Hindiah). They also have workshops wherein are forged the most famous sabres in the world. …It is not possible to find anything to surpass the edge that you get from Indian steel (al-hadid al-Hindi)’*

The mention of Hindvi or Hinduwani steel found in Arabic accounts may be taken to geographically signify that India was known to the West Asians as Hindustan or the land to the east of the Sindhu river. The term Hinduwani became Europeanised to the more stylish and French sounding ‘Ondanique’. Arab accounts also point to the fame of ‘Teling’ steel, which can be taken to refer to the region of Telengana in Andhra Pradesh in South Western India. Indeed the Golconda region of Andhra Pradesh was clearly a nodal centre for the export of wootz steel to West Asia. The Prophet Muhammed, the revered founder of the Islamic faith in the 8th century, is also said to have had a sword made from such steel. This gives an idea of the exalted status of Indian steel. The letters of Jewish merchants from Cairo of the 12th century also point to the export of iron and steel from the Malabar and Coromandel coasts to ports in West Asia. A description from the Crusades, of the Damascus blades went as follows: 'One blow of a Damascus sword would cleave a European helmet without turning the edge or cut through a silk handkerchief drawn across it'.

Literary Fame of Bulat and Ondanique

A. R. Zaky mentions in his book of 1979 on ‘Medieval Arab Arms’ that the Arabs took ingots of wootz steel from India to Damascus following which a thriving industry developed there of making weapons and armour of this steel. Wootz steel after export to West Asia was known as poulad. This has also come to be known as bulat, a common usage in Russia. Of course, another place, which has become synonymous with wootz/Damascus steel, is Syria. Although it seems to be a mistaken notion that Damascus steel was manufactured in Syria, it is the fame of the swords manufactured at the great Syrian capital of Damascus, which has given wootz steel/poulad/bulat steel the name Damask or Damascus steel.

It is interesting to explore the background to the rise of metallurgy in ancient Syria, which gave rise to the fame of Damascus swords. Syria came under the influence of the sophisticated culture and metallurgy of Egypt from the time of the Pharaoh Tutmos III, who ruled in Egypt around 1525-1473 BC. He waged continuous wars with Syria as a result of which Syrian towns came under the rule of Egyptians for many years. Certainly by the early medieval period, trade connections of Syrian towns with India apart from those in Persia and other countries, seems to have promoted the production of Damascus swords. Damascus, Syria's richest cultural centre, is said to have widely traded with the Indian town of Koch, in which a lot of metal shops are said to have been located. Koch may refer to Kutch and there are late medieval accounts indicating wootz steel was carried from Nirmal in Andhra Pradesh in South Eastern India to Kutch on the west coast for export, as it was a trading port looking out towards West Asia. The production of different types of 'bulat' swords was a secret of individual master swordsmiths. Hence, different types of bulat were distinguished by names of numerous locations such as 'taban', 'kara-taban', 'harasan', 'tyndy' and 'sham. 'Sham' is the Turkish name of Syria, suggesting that this type of sword was produced in Damascus. The name 'Damask' later became a generalized term for the bulat.

A celebrated legend concerning Damascus blades is described in a novel 'The Talisman' written in 1825 by Sir Walter Scott, the celebrated poet and novelist from Scotland. Following the accounts of European travellers, wootz steel and the Damascus sword were attracting a lot of interest in Europe around this time. 'The Talisman' is set in the times of the epic conflict between Christian Europe and the Muslim Middle East during the time of the Crusades. The 'Crusades' that took place between 1096-1300 were so called because the knights of Christian Europe aspired to liberate the Christian Holy Land of Palestine from the Saracens, i.e. Muslim forces. The Talisman fictionalises an encounter between King Richard I of England, known as Lion Heart (1157-1199) and Sultan Saladin during the Third Crusade. Saladin has been hailed in Europe for his moderate and dignified treatment of enemies. Saladin had captured Syria, the land known for Damascus blades, and Jerusalem by 1187. In 1192, Richard I is said to have made peace with Saladin after Richard's capture of Jaffa in Palestine. The story goes that in that encounter, both King Richard and Sultan Saladin where keen to show off to each other the superiority of their blades. To prove that his was the better sword, the King of England took a steel bar one and a half inch thick, laid it on a piece of wood and cut it by a mighty stroke. No notch remained on the sword blade. Then the Sultan drew out of his sheath his tarnished-blue sabre, made of Damascus steel, i.e. wootz steel imported from India, and ordered a down silk pillow to be brought. With one light stroke he cut the pillow into two parts, which, as it seemed to everyone, had fallen apart on its own, without any effort on the part of the Sultan. Then the Sultan took off his shawl, folded it into two, hung it on his sabre, threw it up and cut it into two pieces with a sudden stroke!! These accounts point to the incredible sharpness of the Damascus sword blades. The pattern on the sword also drew the attention, as famously described in the Talisman by Sir Walter Scott:

'(The Sultan) drew scimitar across the cushion… with so little apparent effort that the cushion seemed to fall asunder rather than to be divided by violence…(The Sultan had) a curved and narrow blade which glittered not like the swords of the Franks, but was, on the contrary, of a dull blue colour, marked with ten millions of meandering lines'.

This episode from the Crusades between Saladin and Richard is delightfully captured in Figure 18 in what may be described as the 'flashing of swords' rather than a clash of civilizations.

The celebrated Russian writer Alexander Sergeevich Pushkin (1799-1837), who seems to have been familiar with the true bulat (wootz steel) weapon, wrote a little poem dedicated to bulat entitled "Gold and Bulat". Pushkin is credited to have created the genre of modern Russian literature. Pushkin's fascination with bulat swords can be explained if one looks at his life history. He was born of a noble family and was a captive in Abyssinia. He became a general before he went on to become one of Russia's greatest literary figures. Ironically he died by the sword too, reportedly in a fencing duel. The influence on Pushkin of Walter Scott's novel 'The Talisman' may be discerned in a poem of the same name written by Pushkin, also against the backdrop of the Muslim Orient. The poem 'Gold and Bulat' can wryly be interpreted as metaphorically conveying that, all told, the weapon remains mightier than either riches or money. On a more literal note it can indicate that bulat was a material to be valued more than even gold.

Another well known Russian writer who closely followed in the footsteps of Pushkin, probably even to the extent of dying by the sword and shared Pushkin's fascination with bulat was Mikhail Lermontov. He also wrote a poem to bulat. He had ruffled the feathers of Russian authorities merely because, although he was an officer, he undertook to keep Pushkin's legacy of poetry alive. Thus he was transferred in 1837 to Georgia, to fight in the battle zone against the fierce Chechens where he died at the age of 26. His best-known novel, 'A Hero of our Times' is set in these wild Caucasian mountains to which he had been exiled. Indeed, he seems to have encountered the bulat steel in these rather more oriental, Muslim-dominated Chechen regions, leading to an interest in the untold secrets of bulat steel and sword production. He devoted to the bulat the following lines in his poem 'The Poet' (1838) which is suggestive of the great mystique of bulat swords, with its manufacturing techniques clothed in secrecy:

"My dagger is glowing with golden decoration;
The blade is reliable without a flaw;
Its bulat keeps secret hardening –
Martial heritage of Orient".

Around the time of Lermontov's writings in the early 19th century, Muslim-dominated Chechnya in the former Soviet Union shared cultural links with the Oriental Islamic Central Asia and Turkey. Consequently the manufacture of swords and daggers of 'damask' steel used to be a prestigious occupation of master swordsmiths with closely guarded family secrets. In fact, the reverence for bulat or Damascus steel was so high in Chechnya that it has become a part of male Chechen names conveying the attributes of a 'man of steel'! Such evocative Chechen names range from shchokbulat, (snow leopard bulat), hasbulat (beautiful bulat), sambulat (watchful bulat), dzambulat (battle axe bulat), arbulat (black bulat), and such like. There is even a Chechen legend about an ancient Chechen arms smith who mastered the secret of forging damask blades of this steel only to discover that they were so sharp that they could even easily cut off the anvil horn used for forging! The anvil is the base-most often made of iron- against which iron implements were forged as still seen in rural India. Coming back to the legend, the Chechen blacksmith is said to have never again made the damask swords from bulat steel because he feared the consequences if such weapons fell into the wrong hands. There may be a cautionary tale here for enthusiasts or students of blacksmithy wishing to experimentally forge Damascus blades. They had better first devise a shatter proof anvil!

Another term, Ondanique, an Europeanisation of the term Hinduwani used by the Arabs to describe Indian steel, has also had an exotic appeal and literary life of its own. The fabled accounts of Ondanique are often attributed to the quixotic Venetian Marco Polo who is said to have travelled east all the way to China to the land of ‘Kublai Khan’. This is well captured in a poem of 1999 by Philip A. Ellis entitled ‘An Old Warrior to His Grandson’, not only exhorting the child to be fearless but also re-assuring him that in times of danger, there could be no more highly valued asset and enemy-buster in the world than a sword of the fabled Ondanique.

Take up your sword of ondanique,
When times of darkness grow too great
Beneath the stars of eld Zothique…

When nears the pirate’s black caïque
defy the errant whim of fate-
take up your sword of ondanique…

Between, my child, heed this critique,
When danger nears, don’t hesitate:
take up your sword of ondanique
beneath the stars of eld Zothique.

A Continuing Literary Saga

The fascination for wootz steel and the Damascus sword is an enduring one. In the present era this is captured in various media such as novels, movies, teleserials and computer games. The Crusades figure in films by Cecil B. DeMille (the Crusades, 1935), Ingmar Bergman (The Seventh Seal, 1957), and Terry Gilliam (Monty Python and the Holy Grail, 1975). A recent novel entitled “The Confusion” by Neal Stephenson published in 2004, an eight hundred and fifteen page book with many of the characters based on historical fact, accurately narrates much of the science underlying wootz steel.

Chapter 5:

Crucible Steel and Indian Armoury: Sixteenth to Nineteenth Century Accounts

‘The workmanship of the native hilts
can scarcely be surpassed…
The districts of Salem, Koimbatur,
and North Arkat, (in Tamil Nadu, are those)
in which the best Indian steel has been
manufactured from time immemorial…

-M. J. Walhouse, 1878

Semi-industrial Enterprise of Wootz Steel

From the mid 17th century onwards, there are numerous vivid eyewitness accounts of European travellers to the Indian subcontinent. These describe the production of steel by crucible processes spread over different parts of Southern India. These include accounts by Jean Baptiste Tavernier in 1679, Francis Buchanan in 1807, H. W. Voysey in 1832, and others who travelled to locales such as Mysore, Malabar, Salem, Trichy and Golconda. By the late 1600’s shipments running into tens of thousands of wootz ingots were traded out from the Coromandel Coast to Persia. In fact the range of these accounts coming from various parts of Southern India spread over an area of several hundred square kilometres indicates that the activity of manufacturing wootz ingots and selling them across the seas was almost on the scale of a semi-industrial enterprise in an era prior to the Industrial Revolution. While, in the present day information age, places like Bangalore in Southern India have been hitting international headlines as centres for the global outsourcing of software, it seems that a millennium ago the same region of Southern India was a major global centre for outsourcing steel. Indeed some accounts suggest that a large volume of the output of wootz ingots from the Golconda region was intended mainly for export. However, it would be incorrect to conclude that Indian wootz was made solely for export as there are rich traditions of Indian armoury.

Some Insights into Deccan History and Medieval Armoury

The 9th-12th century West Asian accounts of the import to Cairo of iron and steel from the Malabar or Coromandel coasts intriguingly coincide roughly with the era of the great South Indian Hindu dynasties of the Cholas in the Tamil region, famed for their superlative bronze idols, the Chalukyas in the Karnataka region and the Kakatiyas in the Andhra region.

From about 1336 to 1556 the most prominent dynasty in Southern India was the remarkable Vijayanagara dynasty with its once flourishing capital at the site of Hampi in North Karnataka. Its influence spread over most of Southern India. In its heyday, the Vijayanagara dominion was hailed by the Portuguese and Italians such as Paes as the

Rome of the East. They describe its pomp and the bazaars overflowing with riches such as large gemstones, silks and other exotica, especially in the time of its most sagacious ruler Krishnadevaraya. One only has to look at the extraordinary expanse of ruins of palaces, tanks, plinths and sculpted temples hewn of boulders of granite, that hardest of stones stacked all around like gigantic loaves and cakes, to realise that the smiths of that era must have had sharp tools of iron and steel to chisel their way through them. Some of the sculptures at Hampi indicate that women also made up part of the army, wielding weapons and swords. Figure 19 takes artistic license to portray an indolent day for shoppers in the Hampi bazaar.

It is interesting to point out that the occurrence of iron ore in this area has led to steel plants being set up in the twentieth century. One of them is named Jindal Vijayanagar Steel Limited, recalling the glory of the past empire. This plant is one of the three in the world to use a very novel process, known as Corex proces for making iron.

The period around 13th-14th century AD saw the rise to power in Delhi of Muslim Sultanate rule during which time the Gupta era Iron Pillar is thought to have been moved by Iltutmish from Central India and installed in the imposing Qutb Minar complex in Delhi. The 14th century saw the rise of the Deccan Sultanates in peninsular India. They left behind a very refined and distinctive Deccani heritage of Indo-Islamic architecture, painting and culture. The Bahamani Sultanate had been founded in the Northern Deccan parts of Karnataka, Maharashtra and Andhra Pradesh, while the Adilshahi kingdom thrived in North Karnataka from 1510 to 1686. In Golconda, on the outskirts of Hyderabad, the Qutb Shahi dynasty had been established. While Ali Adilshah I (1557-1580) had been a friend of the Vijayanagara ruler, he joined hands with the neighbouring Sultanates to attack Vijayananagara, which was sacked and plundered over several months. This has been described by some Mediterranean travellers. There are several European travellers' accounts of the 17th century describing the brisk trade in wootz ingots between the kingdom of Golconda and Persia during the reign of the Shia Qutb Shahi rulers. Figure 20 is a sketch of a fine Deccani painting depicting how even during a romantic rendezvous the sword had to be kept close at hand!

Around 1556, Akbar took over the reigns of the Mughal dynasty (established in 1526 by the Central Asian, Babar after the battle of Panipat) and ruled from Agra. He became the most illustrious Mughal emperor. Apart from military conquests, Akbar also forged conciliatory alliances, some through matrimony with the Hindu Rajputs who had originally been bitter Mughal adversaries. He expanded the Mughal Empire to cover most of Northern India stretching from Kandahar in Afghanisan to Bengal. Akbar had a broad-minded interest in inter-faith dialogue and ushered in a splendid and unrivalled era of Mughal art, painting and architecture synthesizing Hindu, Jain, Rajput and Islamic motifs as exemplified by his fort-city of Fatehpur Sikri. This legacy was carried forward by his part-Rajput progeny Jehangir and Shah Jahan to its zenith as famously symbolised by the Taj Mahal, rated as the most beautiful monument in the world. The parts of the Deccan ruled by the Deccan Sultans also came under mughal soverignity. The art of the Rajputs, who had their own very vibrant aesthetic tradition, and the art of the Mughals inspired by a refined Saracenic and Persian sensibility, enriched each other in a mutual symbiosis. It resulted in a remarkable efflorescence of Mughal and Rajput art and architecture in the late medieval period.

The Ain-i-Akbari, collated by Abul Fazl, is a major work on the arsenal in Akbar's time. Indeed, the Ain-I-Akbari also gives some idea of the making of steel by crucible processes, whereby the crucibles were fired inside large furnaces in the area south of the Godavari River such as Nirmal and Konasamudram in Andhra Pradesh. Egerton gives a translation of Abul Fazl's account, which gives an idea of the array of personal swords that Akbar alone had which were also graded in importance:

'All weapons for the use of his majesty have names and a proper rank is assigned to them. There are 30 kacah swords…There are also in readiness 40 other swords, which they call 'Kotal' out of the complement of 30 is made up.'

Several impressive collections of Mughal and Rajput Armoury including true watered Damascus blades and pattern-welded Damask blades are to be found in the Prince of Wales Museum, Mumbai and National Museum, New Delhi and also in the various armouries in the palaces and forts of Rajasthan such as those in Jaipur and Alwar. J D Vehoeven has examined in 2004 some of the wootz ingots from the Alwar armoury.

At the end of the 17th century, the Mughal Empire was in the hands of Aurangzeb. It was then that the might of the Mughals was seriously challenged by the spirited Marathas of the Western Indian peninsula. They were better prepared than the Mughals, to cope with the hilly terrain with their lighter equipment and more active cavalry. While the Marathas were previously mercenaries under the Deccan Sultans, it took the genius and valour of Shivaji to organise them into a formidable fighting force that could thwart Mughal complacency. Egerton's accounts indicate that Shivaji was not only skilled in the use of various daggers and swords common in the Deccan, but that he had recruited a fierce fighting infantry consisting of skilled marksmen and swordsmen who hailed from the southwestern ghats and the Deccan (Figure 21). His skill in guerilla tactics was demonstrated in a successful plot to murder Afzal Khan, the general of the army of the Bijapur Sultans who were now vassals of the Mughals, after inviting him to a meeting. Shivaji concealed a dagger called 'bichwa' or scorpion in his sleeve and a 'waghnak', a weapon with blades curved like tiger claws and it proved to be a rendezvous with death for Afzal Khan. By the time of Aurangzeb's death in 1705, his authority was challenged almost everywhere leading to the break-up of the Mughal Empire. In Tamil Nadu the Nayaks, the feudatories of the Vijayanagara rulers, had ruled, from the mid 17th to mid 19th century. Thanjavur came under the Maratha Bhonsle rulers, with the best known of the Bhonsle rulers being Sarfoji. He was a learned scholar, a surgeon and collector and maintained an excellent library as well as a good armoury at the Saraswati Mahal.

Resistance to Colonisation and the Indian Mutiny

In the 1600's and 1700's the trading firms of the Dutch, French and British East India companies were formed to take advantage of the lucrative opportunities of trade with India. Eventually these companies gained political control as seen with the Dutch in

Indonesia. While the French lost out to the British, East India Company, by a mixture of aggression and scheming, expanded in India to rule most of it. One of the rulers who resisted British hegemony was Tipu Sultan of Mysore with travellers' accounts testifying to the manufacture of wootz steel in his domain. While the brave Rani of Jhansi, who died fighting the British in 1857, has become part of Indian folklore, there is another sword-wielding sari-clad unsung heroine, Rani Chennama of Kittur in Karnataka who fought in 1824 against the British to win a battle although she was later captured and killed in 1829.

In 1857, the Indian sepoys employed by the Company, embittered by the brazen British annexations and offences to religious sensibilities, revolted against their British officers. The Mutiny, which began in Meerut and spread to Delhi and other regiments in Upper and Central India, was put down with the arrival of British reinforcements in 1858. This was soon followed by the Company's affairs being taken over by the British government.

The history of wootz steel had a decisive impact, as scores of Indian weapons and armoury were destroyed in the disarmament drive of the sepoys that followed the Mutiny. So highly reputed were the Indian swords made of 'wootz' steel and their cutting edge that the martial threat posed by them was recognised even by the British colonial powers, who seem to have gone to great lengths to counter it. It has even been recorded that, during and following the Indian mutiny against the British of 1857, the British ordered the destruction of all the 'wootz' steel swords. In fact, a special shearing machine was developed for the purpose. It is also said that often the shearing blades of the machine themselves got cut by the tough 'wootz' steel swords, and the British then had to devise a method of inserting the swords into the machine that would protect the shearing blades of the machine. Figure 22 illustrates such a moment where the British after the mutiny are pictured trying to shear and destroy the arms and weapons of wootz steel!

Accounts from Andhra and the Export of Wootz

In the mid-seventeenth century the Venetian, Niccolao Manucci, travelled around various parts of India such as Bijapur, Golconda, Gwalior and Dholapur. He recorded that by 1657 India has exported over 10,000 pounds of steel. In 1679, Tavernier wrote about his travels in the work 'Les Six Voyages de Jean Baptiste Tavernier en Turquie, en Perse, et aux Indes'. There is a description of Persian artisans using steel from Golconda for their blades. Voysey in 1832 came across a merchant from Isfahan in Persia at Konasamudram who was exporting this steel to Persia. The following passage indicates the great demand for this Golconda steel and its uniqueness.

'This steel (from Golconda) is sold in pieces as large as our one-sou loaves and in order to know that it is good and that there is no fraud involved, they cut it in two, each fragment being enough to make one saber … One of these loaves of Steel, which would not have cost more than the value of five or six sous in Golconda, is worth four or five abassis in Persia and the further away one gets the more expensive it becomes: because in Turkey they sell a loaf for up to three piastres, and it also comes to Constantinople, to Smyrna, to Aleppo, and to Damascus where anciently it was transported most, when the

commerce of the Indies came to Cairo via the Red Sea. But today either the king of Golconda makes difficulties about letting steel leave his country or the king of Persia tries to prevent anyone from re-exporting that which has entered his Kingdom.'

By 1667 over five lakh pounds of ironware were exported out of the Andhra region. By the 1660's the Dutch also became involved in developing the iron industry in the Godavari delta of Andhra Pradesh. Indeed in the 17th century the Dutch Establishment is reported to have shipped from India hundreds of thousands of ingots of wootz steel. The Dutch traded in wootz from the east-coast port of Machilipatnam to Gamroan in Persia. It is believed that one shipment in the l600s alone contained 20,000 wootz ingots, where each ingot weighed about one pound. Writing in 1960, H. Maryon mentions that Indian steel ingots were carried inland from Hyderabad to the ports of Cutch, on the west coast of India, and exported to Persia, Syria, and East Africa from where they found their way into Europe.

Accounts of Wootz from Mysore and the Saga of Tipu's Swords

Some of the most detailed accounts from the south of India for the making of wootz steel from the turn of early 19th century come from the travelogue of Francis Buchanan entitled 'A Journey through Madras, Mysore, Canara and Malabar'. Buchanan seems to have toured the Mysore region just after the fall of that colourful ruler of Mysore, Tipu Sultan. Tipu, whose eventful reign lasted from 1782 to 1799, fought in four Anglo-Mysore wars. He died on 4 May 1799 fighting the British forces, when they stormed his fort at Srirangapatnam.

Tipu's resistance was remarkable in the context of the latter half of the 18th century when the British East India Company was aggressively expanding its territory after annexing Bengal, Bihar, Oudh and the Carnatic. Tipu is said to have uttered the famous last words 'it is better to live for a day as a tiger, than live as a sheep for a lifetime', earning the sobriquet of the Tiger of Mysore. Tipu lavishly propagated the tiger motif, such as on his hexagonal golden throne with tiger heads and the famous wooden musical contraption of a tiger devouring an Englishman. This instrument is now in the Victoria and Albert Museum, London. Like Tipu's tiger, the Sword of Tipu Sultan has also become the stuff of legend. Although Buchanan comments that many Hindu temples in the Malabar were destroyed in Tipu's time, there is other evidence in the form of numerous grants and gifts made to Hindu temples to indicate that Tipu, though a devout Muslim, fostered Hindu-Muslim amity. Indeed, his tiger insignia is thought to have been inspired by the local Hindu cult of the patron martial goddess Chamundeshwari of Mysore who rode a tiger.

On the fall of Tipu Sultan, the Asiatic Annual Register of 1799, a record by the colonisers has the following entry: 'A servant, who has survived, relates, that one of the soldiers siezed the Sultaun's sword belt, which was very rich, and attempted to pull it off, that the Sultan, who still held his sword in his hand, made a cut at the soldier with all his remaining strength, and wounded him from the knee.' Soon after, the English troops and officers went on an or orgy of looting for two days; the palaces, priceless jewels and the treasury with bars of gold were plundered and his capital of Seringapatam reduced to ashes. The value of some of the booty was estimated even in those days at pounds 1,143,216. Mohammed Moienuddin in his book ‘Sunset at Srirangapatnam’ writes that,

“… Tipu’s palace was pillaged for his priceless possessions, handkerchiefs and footwear included…”. After the plunder of Tipu’s palace, Lord Colonel Wellesley took charge of Tipu’s personal belongings which included not only swords, firearms and personal jewels but also a set of 84 turbans, 50 pocket handkerchiefs and 26 caps, while his golden throne was broken up”.

The swords of Tipu Sultan have also had an interesting afterlife of their own. The collector Lord Mornington wrote on 19 June 1799 that ‘any sword known to have been used by Tipu would be curious’ and stated that he desired possession of it. Like his other paraphernalia, his swords too bore the royal insignia of tiger stripes. An entry by Malcolm Kaye of 1836 records that ‘after the capture of Seringapatam and the death of Tipu, he purchased a Sultan’s sword which had become prize property.’ Indeed the swords of Tipu remain in high demand and keep turning up at auctions abroad. These include a sword auctioned by Christie’s London in 1995, while another presented to the 4th Duke of Richmond and later by him to the Wodeyar Maharaja of Mysore went missing and was later retrieved from an antique dealer. Most recently in 2004, one of Tipu’s swords, auctioned in Britian, was displayed during an election rally brandished by the successful bidder, industrialist-politician Vijay Mallya from Karnataka, purchased for a princely sum of Rs. 1.5 crores. Figure 23 shows the Sword of Tipu Sultan. This was made in Mysore around 1782. The blued steel hilt inlaid with gold has inscriptions of Koranic quotations to convey victory in battle. Tiger-head langets are inlaid with gold calligraphy and defines the name ‘Ali”. Figure 24 depicts a proud Tipu, seated on his fabled Tiger Throne and looking at a choice collection of swords while the sculpture-cum-organ of the Tipu’s Tiger with the Englishman being mauled gives a plaintive cry in the background!

Buchanan in his travelogue claims to have toured Tipu’s territory on June 13 1800, a year after the fall of Tipu. About iron working under Tipu’s reign, he writes:

‘There were numerous iron smelting furnaces and forges around Channapatna. The finished products are being used for the manufacture of arms and the employing of a large number of workmen. Tipu took it from the workmen at 3 Fanams a Maund or 9 shillings 3 and 1/4 pence a hundred weight. He gave them however, great employment. The furnace is constructed in a hut and consists of a horizontal pit and a vertical fireplace, sunk below the ground level. The ash pit is about 3/4 of a cubit in width and height, and conducts from the lower part of the fireplace to the outer side of the hut, where it ends in a square pit, used for drawing ashes. The fireplace is a circular pit that descends from the surface of the ground to the bottom of the ash-pit. Its mouth is a little dilated. Parallel to the ash-pit, and a little distance from the mouth of the fireplace, a mud wall is erected, in order to shield the workman from the sparks and glare of the fire. The mud wall is about five feet high. Through the bottom of this passes an earthen tube, which conducts into the fireplace the wind of two bellows, each made of bullocks’ hide. The crucibles are made, in a conical form, of unbaked clay.

According to Buchanan's account the crucibles were made by finely churning the necessary ingredients under the feet of stomping bullocks like clay and charcoal. The crucibles were then loaded with iron of about 9-14 ounces in weight along with pieces of tangayree wood. These were packed and heated using bellows for a minimum of six hours. The details of the furnace described and sketched by Buchanan in 1807 indicate that these crucibles were packed in rows of about fifteen inside a sunken pit filled with ash to constitute the furnace which was operated by bellows of the buffalo hide, fixed into a perforated wall which separated them from the furnace probably to minimize fire hazards. The fire was stoked from a circular pit, which was connected to the bottom of the ash pit. The crucibles themselves, were conical and made of unbaked clay, could contain up to 14 oz. of iron, along with stems and leaves. The pieces were then recovered from the crucibles and hammered under heat into small bars. Figure 25 is a conjectural sketch of a view of Buchanan's furnace.

Apart from such accounts, there is another astonishing piece of information that points to the large scale nature of iron mining activity spread over Karnataka alone. It appears that an effort was made during the middle of the 19th century to tabulate the number of mines and furnaces for iron working in the districts of Shimoga, Kadur and Chitaldrug. Valentine Ball commented that 'it is incredible that in the years between 1872 and 1875 there were upwards of 1400 mines'.

Tipu made use of his mastery of metallurgy for fashioning rockets. In a millennium essay in Nature, Roddam Narasimha, National Institute of Advanced Studies has drawn attention to the devastating effect Tipu's rockets had on the British. A celebrated victim of this was Colonel Arthur Wellesley (later Duke of Wellington and the hero of Waterloo). Tipu's rocket corps had 5000 soldiers. The rockets could reach 2.5 kilometeres with a fair degree of accuracy. As steel was used for casing, it tolerated increased bursting pressure and more propellant. Several Indian rockets were sent to Britain, in a way similar to that of wootz. Colonel William Congreve improved on the Indian technology and produced superior rockets in course of time. As Narasimha remarks, even in the late eighteenth century there were several Indian products technologically superior to Western equivalents, and this was recognised by both sides.

Steel from the Salem and Thanjavur Region in Tamil Nadu

The region of Salem in Central Tamil Nadu seems to have been renowned for its iron and steel works. This is seen, for example, in the 19th century accounts of Major M.J. Walhouse. In his account on the Thanjavur Armoury of the 1870's he makes a special mention of a highly reputed ironsmith from Salem: 'The name of Arunachalam of Salem has been known all over India for the last fifty years. The Shikar (hunting) knives and spearheads made by him could not be excelled and hardly equalled in temper and finish by any English smith. The same might be said of all iron and steel works wrought by his hand.' Several of the native daggers were often curved as still seen in the Thanjavur armoury. They are seen mirrored in a volume on early travels in India between 1583-

1619, edited by William Foster where it is mentioned that ‘their swords are made crooked like a falchion, very sharpe.’

Holland is one of the colonial era travellers in 1892 who observed the production of crucible steel or wootz in Tamil Nadu in the region of Salem and also in Tiruchirappalli. The cakes of steel that Holland observed being made at Salem were sold for 4 or 5 annas in the bazaar, while he describes crucibles from Tiruchirapalli as being ‘something like a large pear, 5” in length and 3’ in diameter at the widest part’, i.e. something approaching a conical shape.

The tales of pillage and plunder of treasures by India’s colonial masters such as those recounted previously make for sad reading. Ironically, the acts of spiriting away artefacts to England have in the long term contributed to the much more effective preservation of such artefacts for posterity. This is not the case of artefacts left behind in India. Consider for example, the regret expressed by the Lord Egerton of Tatton, writing in his book ‘A description of Indian and Oriental Armour’, of the collections taken to the Tower of London and the India Museum:

‘Neither collection is rich in Southern Indian arms, and it is a matter of regret that the Government of India, while professing to watch over the preservation of archaeological remains, has neglected to take advantage of the opportunity of acquiring old weapons from the armouries at Tanjore and Madras, and allowed them to be broken up and the contents sold as old metal’.

A feature of armoury from the Thanjavur region was that there were several examples of intricately carved hilts often with exquisite figurative art. Figure 26 is a sketch of such a hilt from the Thanjavur armoury adapted from Egerton.

On Indian-made Damascus blades

While the technology of making high carbon wootz steel by crucible processes, perfected in Southern India, is a remarkable story, no less outstanding a feat was the craft of making sword blades from wootz steel. Some of the most spectacular jewel-encrusted swords or artefacts of Damascus steel come from Syria, Persia and Ottoman Turkey, and are thought to have been made of wootz steel imported from India. Indeed, the accounts of travellers from Tavernier to Voysey from the 17th-19th century record the involvement of Isfahanis or Persians from Isfahan in the trade in wootz ingots from Golconda in southwestern India. There is a misconception that Damascus swords are a West Asian tradition with only ingots made in India. However, there are numerous Indian examples of fine Damascus swords with the characteristic damask patterns, from Mughal India, the armoury of Golconda and Hyderabad’s Nizams, Tipu Sultan’s armoury, Ranjit Singh’armoury, Rajput, Thanjavur and Maratha armoury. Often set in elegantly bejewelled hilts, the ‘Damascus’ sword can be an object of great refinement and beauty.

Swords and daggers were made of wootz up until the 19th century wootz or Damascus steel was made at numerous centres all around the subcontinent. These centres included Golconda and Mysore in Southern India, which were also amongst the best known centres for making wootz steel ingots. Other centers include Gwalior, Thanjavur, Lahore, Mysore, Agra, Jaipur and Amritsar. An array of different types of Damascus sword patterns has been identified. Pant identified a new design from blades kept in the collection of the Salar Jung Museum in Hyderabad of the period of the Nizams of Hyderabad. Sadly, with the demise of the craft of making the requisite wootz steel itself, the craft of making Damascus blades also died out sometime in the 19th century and does not survive today at any of these centres.

Little also survives in terms of accounts of the swordsmiths themselves apart from occassional writings such as Egerton's observations on the skills of the Hindu swordsmith Arunachalam from Thanjavur. Some of Tipu's 18th century swords such as the one gifted by the Duke of Richmond to the Wodeyar Maharaja of Mysore bear an inscription naming the maker as the Muslim bladesmith Gul Asadullah Isfahani. Although this name suggests a Persian artisan from Isfahan, in fact many Indian artisans are known to have signed their names as Asadullah, after a legendary 16th century Persian blacksmith, reflecting the reverence for Persian blacksmithy. Pant and Sachse mentioned their interactions some decades ago with the Hindu family of Gopilal in Udaipur, a well-known maker of welded-Damascus blades. What the above does suggest, however, is that not only Muslim but also Hindu artisans in the Indian subcontinent excelled at swordsmithy. This runs counter to the perception of Damascus blades as a preserve of Islamic West Asia.

One dagger found (Figure 27) in a collection in Ootacumund in Tamil Nadu had a blade with the characteristic fine wavy pattern, which indicated that it was a blade made of wootz high-carbon steel. The hilt was made of 'bidriware', an etched high-zinc alloy with over 90% zinc, and very finely inlaid in silver and was a good indication that the sword was of of South Indian provenance. This dagger is also rich in symbolism. It represents two great metallurgical innovations that seem to have had their origins in the genius of pre-Islamic Hindu India. One is that of producing high-carbon wootz steel, and the other is the extraction of metallic zinc. Both flourished to reach their artistic and technical zenith in Islamic India as seen in the decorative use of the elegant bidri alloy and of etched Damascus steel. Thus, this dagger is a fine symbol of the synergetic interactions between Hindu and Islamic traditions in the Indian subcontinent.

Chapter 6

European Excitement: Sixteenth to Early Twentieth Century Experiments

‘..there is a cake which is supposed
to be steel from India and the kind
to be rated most highly in Egypt.
I could find no artisan in Paris
who succeeded in forging a tool out of it.’

-Rene Antoine Ferchault de Reaumur, *1722*
cited by A. G. Sisco and C. S. Smith 1956

A Revolution in Materials Science

In many ways the advent of wootz steel and the Damascus blade bear all the marks of an industrial revolution. They brought about a paradigm change in the availability of an advanced material in the form of steel and an industrial product, the sword, which changed the fortunes of nations. It differed from the first industrial revolution in that the method of production by the crucible method did not lend itself to mass production. Thus its impact was profound but not overwhelming. It is interesting to observe that both the crucible method and related sword making were essentially empirical exercises without any benefit of scientific understanding. In hindsight it is astonishing that such a major technological change could occur without preceding scientific investigations. In recent times there are many parallels, where technology led the scientific studies. Thus the making of cannon led to the discovery of thermodynamic principles and not vice versa. Even Bessemer’s invention of the converter for making steel – perhaps comparable in scope to the transformation in human civilisation to the discovery of the silicon chip - was made on the basis of an incomplete technical education!

The scientific revolution was a European event that followed the Italian Renaissance displacing the dark clouds of the Middle Ages. It primarily occurred in England, where the industrial revolution also had its staging. These major tectonic changes in the way of the functioning of societies led to European ascendancy and the colonisation of the rest of the world. There was, thus, a general reversal of fortunes. It is difficult to believe that in the past the Mughal Empire in India and the Aztec empire in Mesoamericas were far more prosperous than most of Europe.

Even though European nations were familiar with the Damascus sword from the Crusades, it is the intimate association of England as a colonial power with India that brought the study of wootz steel onto centre stage. This advanced material produced by the natives of India astonished their British masters. Thus, a scientific study began in Europe and essentially led to the discovery of the basic principles of materials science. In particular the crucial link between composition, structure, microstructure, processing, the shape of the product and properties was established.

Heady Days of Early Metallurgical Studies on Wootz

Some of the best-known medieval texts on metallurgy are the Pirotecchnica by Birunggio and De Re Metallica by Agricola. Even though these two authoritative treatises make reference to steel, they fail to distinguish between iron and steel. There was also no major treatment of either wootz steel or the Damascus sword, as can be inferred from C. S. Smith's papers.

The 18th, 19th and early 20th century saw a heady period of European interest in trying to understand the nature and properties of wootz steel. Indian wootz engaged the attention of some of the best-known scientists. One was Michael Faraday, inventor of electricity and one of the greatest of the early experimenters and materials scientist. He was a blacksmith's son and was fascinated by wootz steel. He worked with James Stodart as a chemical assistant at the Royal Institution, London. Stodart was a Fellow of the Royal Society and a cutler by profession. Together Stodart and Faraday undertook to analyse wootz or Indian steel. To replicate wootz and to better understand the properties and alloys of steel, Stodart and Faraday made several experiments alloying Indian steel to various constituents including rare earth elements such as rhodium and noble elements such as platinum.

Some the early experiments such as those undertaken by Faraday and Breant in the early 19th century are described. This should be of interest to students as they give a flavour of the diligence and excitement with which the early metallurgists went about mixing, alloying, casting, etching, forging and experimenting with materials in an era before microscopes were even properly developed. It is also amazing that, whereas previously less than a dozen elements had been used in antiquity, already by this time new elements of the Periodic Table were being identified at an almost exponential rate. In their studies on wootz, these scientists seized the opportunity of experimenting with many of the rare earth or newly identified element such as rhodium, osmium, palladium, uranium and platinum. Hence these studies relating to Indian steel capture a special moment in metallurgical history.

Impact of Early Accounts of Indian Cake of Steel

The first recorded scientific observation on wootz may be that of the Italian Giambattista Della Porta, an inimitable naturalist of Venice. In 1589 he highlighted the importance of temperature in the heat treatment of wootz by emphasising that "too much heat makes it crumble". This was followed by Joseph Moxon's observations in England in 1677. He cautioned against forging this steel above a red heat. The experiments which sparked European imagination and interest in studying wootz steel in the early 18th century were those of the French metal smith/scientist/philosopher Rene Antoine Ferchault de Reaumur. Reaumur, who was employed by the Duke of Orleans, wrote in 1722 his 'Memoirs on Iron and Steel'. Earlier books on metallurgy dealt mostly with noble metals. This is the first book on iron in history. Reaumur wrote about an intriguing 'cake of steel' from India. As translated and reported by A. G. Sisco and Smith's paper of 1956:

His Royal Highness the Duc d'Orleans himself give orders that the steels of which the famous Damascus swords are made be sent to me from Cairo…Among the steels which I received from him, and which he assured me were the best, there is a cake which is supposed to be steel from India and the kind to be rated most highly in Egypt. I could find no artisan in Paris who succeeded in forging a tool out of it…

Reaumur's account clearly points to the highest repute of the Indian steel amongst the sword makers of the Middle East and the difficulties faced by European artisans in attempting to forge this steel. The great reputation of this pre-industrial Indian steel in Europe is also exemplified by its sale in Hamburg in the 18th century as Indian steel.

It was probably the investigations of George Pearson in 1795 reported at the Royal Society, which had the most far-reaching impact in terms of kindling interest amongst European scientists in wootz. He reported on 'a kind of steel from Bombay called wootz'. Of course, as various scholars have clarified, wootz was never actually manufactured in Bombay, that vibrant port city on the west coast of India (now called Mumbai). This term 'Bombay wootz', which also persists in later papers by James Stodart and Michael Faraday of the 1820's seems to have derived from Pearson's communications since he received specimens of wootz from a source in Bombay. George Pearson rightly concluded that wootz was more like steel than iron but erroneously concluded that it owed its properties to the presence of oxygen, which also set it apart from steel.

Lardner who wrote the paper 'A Treatise on the Progressive Improvement of the Manufacture of Metal' published in 1842 points to Tavernier's mid 17th century travel account that 'the steel susceptible of being damasked comes from the kingdom of Golconda. It is met with in commerce in lumps about the size of a halfpenny cake'. Lardner adds that 'from this account it is evident that the Golconda steel was in buttons like wootz'. Thus it was established that wootz, quaintly described as 'cakes' and 'buttons', was the same as the steel that was exported to Persia from Golconda in the 17th century for making the damasked blades or Damascus blades.

Identification of Carbon in Steel due to Studies on Damascus Steel

Although iron and steel had been used for centuries, it was not appreciated until the 18th century studies in Europe that it was the role of carbon in steel as the dominant element which resulted in its improved properties over wrought iron. The role of carbon in steel was unveiled by Swedish metallurgists by the latter half of the 18th century. Apart from the 'true' and welded Damascus blades, amongst the textured or patterned oriental blades were the elegant Japanese swords which were made be repeatedly welding composites of low and high carbon iron or steel followed by etching. A Swedish metallurgist guessed that there was carbon in steel on observation of the black and white etching of the steel and iron parts of 'welded' or composite Damascus blades and thereafter interest in replicating true Damascus steels followed. Swedish studies received an impetus with the setting up of a factory to make gun barrels of welded Damascus steels.

To quote Cyril Stanley Smith: ‘In 1774 the Swedish metallurgist Rinman (inspired by a paper on the manufacture of gun barrels from welded composites in the manner that originated in the orient but was being successfully duplicated in his country) carried out extensive studies on ‘the action of acid on different kinds of iron and steel’. He showed that wrought iron dissolved completely but there was a definite residue after the solution of steel or cast iron. This residue which was described as a ‘plumbago-like’ substance was nothing but carbon. Thereafter the great Swedish chemist Tobern Bergman in 1781 was able to extend Rinman’s idea and quantitatively determine that the compositions of cast iron, steel and wrought iron varied due to the composition of ‘plumbago’ i.e. graphite or carbon. It would not be out of place to say the role of carbon in steel was discovered partly due to the interest in oriental steels and swords such as true Damascus steel and welded Damascus steel.

Studies in the twentieth century have added to this knowledge. In 1956 the Royal School of Mines in England undertook to examine some ingots of wootz steel. They had been procured at the end of the nineteenth century from the Indian subcontinent Sir Thomas Holland. He had observed the making of wootz steel in the region of Tiruchirapalli in Tamil Nadu making it the likely source of the ingots and crucibles. A cross-section of an ingot showed unambiguously that the steel had been completely melted from the large ‘dendritic’ structure. This clearly indicated that the ingot was cast. The network of tree-like branches is known as dendrites.

Another important study on wootz steel was by Panseri. In 1962 he seems to have been one of the first to point out that Damascus steel was a hypereutectoid steel with spheroidised carbides and carbon content between 1.2 and 1.8%. Spheroidisation refers to the process of globulisation that the iron carbide network would have undergone during forging.

Experiments on Wootz and Alloys of Steel by Michael Faraday

Following the Swedish studies, the interest in Damascus steel moved to France and England. After George Pearson’s study, Mushet in 1804 was one of the first to correctly conclude that there was more carbon in wootz steel than in common steel from England, although this idea does not seem to have gained currency until later. Stodart succeeded in forging wooootz steel. He was the first to measure the temperatures corresponding to the colours associated with the tempering of steel. He used wootz in his cutlery business to make knives as reported in 1818 to find that wootz steel had a very fine cutting edge, superior to any other. Faraday joined Stodart and enthusiastically studied wootz between 1819 and 1822. He experimented with various alloys of steel before his interest moved on to the problem of electromagnetism. These investigations were reported in the paper entitled ‘Experiments on the Alloys of Steel, made with a View to its Improvement’ in 1820 and another communication entitled ‘On the Alloys of Steel’ in 1822. Figure 28 is a portrait of Michael Faraday. Figure 29 is a photograph of a specimen of wootz in Science Museum, London. The wootz cakes were about four inches in diameter and two inches in height. Figure 30 shows the dendrites in such a cake.

Stodart and Faraday set about trying to replicate wootz steel by alloying steel with a range of metals. As they say in their paper ‘On the Alloys of Steel’, “together with some others of the metals, the following have been alloyed with both English and Indian steel, and in various proportions; platinum, rhodium, gold, silver, nickel, copper and tin”. They also attempted to make steel by alloying nickel and noble metals like platinum and silver and indeed these studies did show that that the addition of noble metals hardens steel. On the nature of wootz, Stodart and Faraday incorrectly concluded that aluminium oxide and silica additions (i.e. alumine and silex additions) contributed to the properties of the steel:

“By referring to the analysis of wootz, or Indian steel, it will be observed that only a minute portion of the earths alumine and silex (ie. alumina and silica) could be detected, these earths (or their bases giving to the wootz its peculiar character. Being satisfied as to the constituent parts of this excellent steel, it was proposed to attempt making such a combination, and with this view, various experiments were made. Many of them were fruitless:

However, Stodart and Faraday did come around to making one important and accurate observation that the damask pattern that could be produced from wootz was due to the inherent crysal structure and not due to it being a mechanical mixture of two substances:

“We have ascertained, by direct experiment, that the wootz although repeatedly fused, retains the peculiar property of presenting a damasked surface when forged, polished and acted upon by dilute acid. This appearance is apparently produced by a dissection of the crystals by the acid, for though by the hammering the crystals have been bent about, yet their forms may be readily traced through the curved, which the twisting and hammering have produced. From this uniform appearance on the surface of wootz, it is highly probable, that the much-admired sabres of Damascus are made from this steel, and, if this be admitted, there can be little reason to doubt that the damask itself is merely an exhibition of crystallisation. That on wootz it cannot be the effect of the mechanical mixing of two substances, as iron and steel, unequally acted upon by acid, is shown by the circumstances of its admitting re-fusion, without losing its property.

The importance of such studies also stems from the fact that they probably laid the foundations for making alloy steels, which have been very important to the modern day materials revolution. Stodart and Faraday state in their second paper that:

“*The alloys of steel made on a small scale in the laboratory of the Royal Institution proving to be good, and the experiments having excited a very considerable degree of interest both at home and abroad, gave encouragement to attempt the work on a more extended scale, and we have now the pleasure of stating that alloys similar to those made in the Royal Institution, have been made for the purpose of manufacture; and that they prove to be, in point of excellence, in every respect equal, if not superior, to the smaller productions of the laboratory. Previous however, to the extending the work, the former experiments were carefully repeated, and to the results were added some new* *combinations, namely, steel with palladium, steel with iridium, and osmium, and latterly, steel with chromium".*

Figure 31 shows Faraday's symbol for wootz. It appears to be in Devanagari script and could be either Sanskrit or Hindi for Lohar (blacksmith). It is plausible that Faraday copied it from one of the Indian samples.

A reference may also be made to Henry Wilkinson, the famous swordmaker. In 1837 he studied samples from Cutch and Salem. He is credited as the first to make a clear correlation beween the visible crystals on the steel and the subsequent pattern that emerged on forging the steel into a sword.

Studies in France

Jean Jacques Perret was a French cutler, who was well versed with the Damascus steel. In 1771 he wrote a major treatise on The Art of the Cutler with an entire chapter devoted to the method of making steel in the style of Damascus. He was fully aware that he could not reproduce the steel. Faraday's research made a big impact in France where steel research on weapons thrived in the Napoleonic period. The French Revolution and the Napoleonic wars had brought to light the shortcomings of the French arms industry and there was much public support for technology in general and research on arms in particular. The Society d'Encouragement pour l'Industrie Nationale was set up which gave prizes for interesting research. In 1819 the Society awarded a silver medal to a cutler from Marseille, Degrand-Gurgey who exhibited some fine 'textured' Damascus blades, which he made by welding layers of iron and steel with laminae of platinum. In 1820 Stodart and Faraday's paper was translated into French and a special commission was set up to repeat their work.

The Commission was headed by Jean Robert Breant. It got 100 kg of Indian wootz from the East India Company for their research. In 1821, Breant, who was Inspector of Assays at the Paris mint and had played an important role in the production of platinum got interested in Stodart and Faraday's work on wootz and alloys of steel and in trying to duplicate the damask patterns. The struggle is well reflected in the efforts of Breant who in a space of less than six weeks conducted an astonishing number of about 300 experiments on combinations of steel with a range of elements ranging from platinum, gold, silver, copper, tin, zinc, lead, bismuth, manganese, arsenic, boron and even uranium. One can only picture the extraordinary enthusiasm with which these early pioneers of modern metallurgy went about their investigations, often at risk to their health. Breant dangerously experimented with radioactive uranium and was one of the early scientists to do so. He finally also came to the conclusion that the properties of Damascus steel were due to 'carburetted' steel, i.e due the presence of higher carbon than steels previously known in Europe. Figure 32 is a light-hearted bit of imagination of Breant in the thick of his experiments, finally exclaiming "Enfin! (At last!), Experiment No. 301 shows that wootz = iron + carbon!"

In a seminal paper, Breant distinguished the various micro-constituents of steel, now termed as cementite, ferrite and austenite. He also demonstrated how the texture changed with variations in composition, temperature and mechanical deformation. This correlation between these various items constitutes the cornerstone of modern materials science. He was the first to link the texture with the coarse duplex crystals formed by solidification. His paper was briefly withheld from publication for reasons of national security. It was eventually published after two years and was immediately made available in English translation.

Russian Bulat

In 1841-43 in Russia Major General Pavel Anossoff (Figure 33), Engineer of Mines and Director of the Zlatoust Steel Works in the Ural district repeated the work not only of Stodart and Faraday but also of Breant. In fact, Anossoff went to the extent of trying to add diamond, that purest and most prized form of carbon, to steel to make wootz or Damascus steel. Like Faraday before him Anossoff made two hundred trials by alloying iron with platinum, manganese, chromium, titanium, silver and gold.

Even though it is stated that Anossoff seems to have been the first person in Europe to have succeeded in making blades of Damascus steel, Cyril Stanley Smith had reservations about his efforts. According to Nicolai Belaiew, who re-discovered Anasoff's work in 1918, the blades made by Anossoff were even able to cut a gauze handkerchief in midair. Belaiew's work of 1906 and 1918 not only revisited Anossoff's paper 'On the Bulat' but he also gave an account of his own studies on the making of Damascus blades, starting with iron and graphite, along with micrographs. Figure 34 is a portrait of Belaiew. In 1868, D. K. Tschernoff, whose portrait is sketched in Figure 35, undertook to reproduce Breant's experiments. B. Zschokke in 1924 examined the microstructures of actual oriental Damascus blades along with excellent photomicrographs. This may well have been the first time that such microstructures were observed. In the past decade there is revival of interest in Russia. Sergey Lounyov, Moscow Aviation Technological Institute, has tried to follow in the footsteps of Anossoff and replicate Damascus swords.

Anossoff's excitement with 'bulat' steel', captured in the following words, ironically marked the end of the road for the traditional wootz steel enterprise rather than the new beginning he was so enthused about:

'Our warriors will soon be armed with bulat (wootz) blades, our agricultural labourers will till the soil with bulat plough shares, our artisans will use tools fashioned of bulat and bulat will supersede all steel now employed for the manufacture of articles of special hardness and sharpness…'

After the early 20th century there was a lull in the interest in wootz as the Bessemer and Siemens processes were seen as routes to homogeneous steel in bulk quantities. Cyril Stanley Smith in the 1950s to 1960's revived interest in this enigmatic Oriental steel as discussed in the next chapter. Indeed, the excitement and interest in wootz took on another form when it travelled across the Atlantic, following the rising fortunes of America.

Chapter 7

Replication of Wootz: Twentieth Century American Adventures

‘Damascus steel actually consists of
an extremely high-carbon cast steel,
the best swords being forged in Iran
from cakes of steel made in India
and known as wootz’.

-*Cyril Stanley Smith (1963)*
‘Four Outstanding Metallurgical
Researches In Metallurgical History’

Cyril Stanley Smith: Materials Scientist and Art Connoisseur

The interest in wootz and Damascus steel that thrived in Europe until the early twentieth century waned during the period of the two World Wars. Several colonies around the world including India obtained their independence from European occupation. This period also saw a tremendous paradigm shift away from the Old World in terms of weapons and armoury with the emergence of nuclear weapons, the devastating powers of which were demonstrated with the American bombing of Hiroshima and Nagasaki in Japan in the 1940’s. It is interesting to note that Cyril Stanley Smith played a major role as the metallurgist in the Manhattan project. He was primarily responsible for the development of the metallurgy of plutonium, then the latest entrant to the family of metals.

It was after Smith turned his eclectic gaze to archaeological materials that interest in wootz steel was revived. He was not only an expert in materials and metallurgy but a connoisseur with wide interests in art objects and archaeological artefacts and with an abiding appreciation of the oriental heritage. His landmark book, ‘The Search for Structure’, explored not only how the structure of materials can have an artistic dimension but also how the artistic accomplishments of the ancient world and the orient played their part in kindling early interest in studies in metallography and material science. Figure 36 is a portrait of Cyril Stanley Smith. Damascus steel enjoys pride of place in this analysis by Smith, who ranked it amongst the four outstanding metallurgical researches in metallurgical history in his book of 1963. He also pointed out that steel was not commercially melted in Europe until the mid 18th century, and that even this was a ‘textureless’ tool steel with no more than 0.8-1% carbon cast in a metal mould, so that the oriental higher carbon wootz crucible steel process leading to ‘damasked’ blades eluded easy duplication with traveller’s tales in themselves not being adequate.

Special mention must be made of the seminal contributions of Oleg Sherby and Jeff Wadsworth at Stanford University and J. D. Verhoeven at Iowa State University. Their approaches were sharply different. It is stimulating to follow their arguments in scientific journals about the real reason for the damascene effect. The production of

Damascus swords enjoys enormous popularity in the USA. To illustrate this activity reference will be made to the artistry of Ric Fuller.

Studies on Superplasticity of Ultra-High Carbon Steel

Sherby and Wadsworth at Stanford University were interested in developing superplastic ferrous materials. Most known superplastic materials at that time were nonferrous alloys. But what is superplasticity? Superplasticity is a phenomenon whereby an elongation of several hundred percent can be observed in certain alloys in tension, with neck free elongations and without fracture. Superplasticity occurs at high temperatures. What is intriguing is that superplastic materials can be formed into an array of complex shapes. The extent of such elongation can be appreciated, if is is noted that by contrast most crystalline materials can be stretched to no more than 50 to 100 percent. It would probably be like imagining an elastic band which can be pulled to not just double but several times its length. In technical terms, for superplastic materials the index of strain rate sensitivity (m) is high, being around 0.5. At the ideal index of m=1, the flow stress is proportional to the strain rate and the material behaves like a Newtonian viscous fluid such as hot glass. Superplasticity occurs only above 0.3-0.4 Tm K where Tm is the melting point of the material. Another feature is that once super-plastic flow is initiated, the flow stress required to maintain it is very low. Superplastic materials essentially comprise a two-phase material of spherical grains of extremely fine grain size of not more than 5 microns at the working temperature. Such ultrafine-grained materials exhibit grain boundary sliding, yielding superplastic properties. Figure 37 shows the mechanical behaviour of ultra high carbon steels. Figure 38 depicts the ultrafine grained microstructure of an ultra high carbon steel (UHCS) from the investigations of sherby and Wadsworth.

The studies made in the 1970's by Sherby and Wadsworth indicated that UHCS with a carbon content of around 1.5% exhibited superplastic properties. They had no prior knowledge of wootz steel. When their results were presented, a member in the audience pointed out that their composition matched that of wootz steel. This inspired Sherby and Wadsworth to dedicate a major portion of their research into the study of Damascus steel. Materials, which exhibit such properties as superplasticity can be described as advanced materials. For this reason, wootz steel too can be classified as an advanced material of the ancient world.

The studies by Sherby and Wadsworth reported in 1980 indicated that UHCS with 1.8% C showed a strain-rate sensitivity exponent nearing 0.5 at around 750 ºC. Indeed a patent was awarded to the team. The explanation of the superplasticity of the UHCS is that the typical microstructure can lead to a fine uniform distribution of spheroidised cementite particles (0.1 mm diam.) in a fine grained lower carbon ferrite matrix. Such steels are also found to have strength, hardness and wear resistance.

The high strain-rate sensitivity noted for UHCS of a comparable high-carbon content as wootz indicated that wootz steel could well have exhibited superplastic properties at higher temperatures. It is in some ways an irony that a modern day patent was awarded for ultra-high carbon steels, since in reality this was an ancient material, which was produced over many centuries ago in India rather than being a modern innovation!

On Forging Ultra High Carbon Steels

By 1975 Wadsworth and Sherby had found that steels with 1-2.1% C could be both superplastic at warm temperatures and strong and ductile at room temperatures. However, such steels had to be forged in a narrow range of 850-650 ºC and not at white heat of 1200 ºC to get the desired fine grain structure and plasticity.

In fact, this finding also fits in with the observations made by earlier European blacksmiths about the difficulties in forging wootz. The reason why earlier European blacksmiths failed to forge wootz steel or duplicate Damascus blades for some time was because they were in the practice of forging only low carbon steels at white heat. This is because these low carbon steels have a higher melting point. The forging of wootz at high heat would have led to the dissolution of the cementite phase with the result that the steels would have been found to be very brittle and would crumble under the hammer.

Moreover, the degree of spheroidisation was found to affect the strength and ductility of UHCS. With more finely spheroidised carbides, high yield strengths of 800 MPa to 1500 Mpa were observed. On the other hand, UHCS with coarsely spheroidised carbides were especially ductile with up to 23% tensile elongation.

It seems likely that some kind of empirical appreciation on the part of the oriental blacksmiths of the superplastic and superformable properties of ultra-high carbon wootz steel within its limited temperature range made it possible for them to forge these steels. It is not yet known how fully the superplastic properties of this steel were exploited by the ancient blacksmiths of West Asia and India. Several accounts indicate that they were certainly able to manipulate the alloy with a skill that could not be easily replicated by the European experimenters of the 19th century.

An important contribution of these studies has been to establish that the cast structure of wootz steel had to be mechanically worked at a high temperature by methods such as forging to prepare the sword. This process miraculously changed brittle steel into a ductile one by changing the morphology of the cementite from a grain boundary network to a spheroidised one.

‘Re-inventing’ Wootz Blades and Experimental Simulations

Another reputed American team to have undertaken extensive landmark studies in simulating wootz steel is that of Verhoeven and the blacksmith Alfred Pendray. As reported in several papers of 1987, 1990 and 1996, Verhoeven and others have attempted to ‘re-invent’ the Damascus steel and blades with replication experiments based on historical studies of Damascus blades and the composition of wootz ingots.

Verhoeven made careful metallographic examination of the swords of B. Zschokke. He observed that the cementite particles in them were six to nine microns in diameter. These spherical particles were clustered in bands spaced 30 to 70 microns apart and are lined up parallel to the surface of the blade. The particles formed planar arrays. He concentrated on reproducing the chemistry and the banded microstructure of such blades.

Essentially, they attempted to use two methods to make ingots comparable to wootz. One of these consisted of melting iron charge in a small sealed clay graphite crucible inside a gas-fired furnace with the ingot formed by furnace cooling. These were made by rapidly heating the charge and holding it for a period of 20-40 minutes between 1440-1480 ºC followed by cooling at furnace cooling rates or faster. The composition of the charge was chosen to match that of genuine Damascus blades of about 1.6% C and 0.1% P. In 1996, Verhoeven and co-workers also made ingots by a process of vacuum-induced melting whereby the charge was melted by heating to around 1000 ºC, backfilling with nitrogen gas. This was followed by heating to about 1580 ºC and then outgassing for around 5 minutes so that cooling rates at arrest temperature were around 5-100 C/minute.

Although the structures of the ingots so produced do simulate those of Damascus blades, it may be argued that such laboratory simulations might not replicate conditions related to traditional or archaeological processes. For instance, the charge is fired in a very short time in both the methods described above and the melt is cooled very rapidly under modern industrial conditions. This was not achieved traditionally, since the 19th century descriptions of the wootz process suggest a very long firing cycle for the charge. In fact the eye witness descriptions of Voysey and Francis Buchanan of the early 19th century laid emphasis on the fact that the prolonged heating of the charge and its slow cooling were essential for obtaining the optimum results in the wootz process. In any case, however, as pointed out by Verhoeven, as far as cooling rates were concerned, they found these to have no effect on the final outcome of the ingots. The experimental simulations by Verhoeven served to monitor in detail the thermal cycles and cooling curves and composition so as to be able to arrive at a final product which matched that of Damascus blades. An important distinction is that Sherby and Wadsworth relied on mechanical working in the austenitic state and relied on the preciptation of carbide during cooling. Verhoeven produced finer carbides by heating and cooling cycles without any resort to mechanical working.

Vanadium as the Magic Dust in Banded Patterns of Wootz Blades

Verhoeven and Pendray made extraordinary efforts to understand the mechanism of the formation of the pattern of aligned bands on the blades. In 1998, they reported that this was the result of a carbide-banding phenomenon produced by the micro-segregation of minor amounts of carbide-forming elements present in the wootz ingots. Vanadium and manganese were two of the impurities, which played a key role in the banding (Figure 39). They found some Damascus blades including one from India to contain such amounts of vanadium. They also suggested that the damascene patterns could only have been produced from Indian wootz ingots made from the appropriate impurity containing ore deposits.

Verhoeven has also pointed out that their finding that 0.003 percent vanadium is effective in producing iron carbide banding patterns in high-carbon steels seems to have been aided by their accidental use of Sorel metal as a raw material for making ingots. This alloy, which is a high purity iron carbon alloy with about 4% carbon containing vanadium as an impurity, is produced from an ilmenite ore deposit near the St. Lawrence River in America. The authors detected vanadium to be one of the impurities in some seven samples of wootz steel blades analysed by them. This also gave them the idea that the 'watered steel' pattern of carbide banding could have resulted from the presence of vanadium as an impurity in ores from Southern India used for making wootz steel. Indeed some accounts such as those of Tavernier make clear that it was South Indian steel which was sought after in Persia for obtaining the damasked patterns. The significance of such studies lies in the fact that it established the importance of micro-alloying additions in improving the properties of steel. Verhoeven has also advanced the idea that the depletion of vanadium containing iron ores as the main reason for the disappearance of the crucible steel making in South India.

On Forging of High Phosphorus Wootz and Damascus Blades

Another explanation that has been put forth about contributory factors for the banding mechanism is the presence of phosphorus. Wootz blades with 1.3-1.8% carbon analysed by groups such as Zschokke and Verhoeven are also found to contain a fair amount of phosphorus impurities of about 1000 ppm. Brian Gilmour of the Royal Armouries Museum, had metallographically investigated Damascus blades from Persia and has written an authoritative book on Persian metal technology. He has indicated that phosphorus impurities may have contributed to the banding effect.

The re-invented wootz ingots made by Verhoeven and his team, were also made with significant phosphorus content of up to 0.1%, similar to genuine Damascus blades. Such a high phosporus level would also have contributed to the ingots being hot-short or difficult to forge. This would explain why according to several accounts bladesmiths in Europe could not forge blades out of wootz ingots. Accounts such as those of Moxon in 1677 indicate that wootz was one of the most difficult of steels to work at the forge, but that since this steel mostly came in the wrought form to England, it was found to have a finer and stronger edge than other steels.

To overcome this problem the ingots made by Verhoeven and his colleagues were held at 1200 ºC in iron oxide to produce a protective rim of pure iron around the ingot. This was ductile so that the ingot could be forged. Ingots were also made with the phosphorus levels reduced to the point where the ingots were not hot short and thus eliminated the need for the rim heat treatment.

Simple Steps to Make Wootz and Damascus Blades

Alfred Pendray outlined some simple steps to make wootz and a Damascus blade in an article 'The Mystery of Damascus blades' by Verhoeven in the Scientific American.

Firstly, Pendray recommends the use of high-purity iron, charcoal, glass chips and green leaves and sorel iron (with vanadium impurities) to be loaded in the crucible for firing. This is a process of carburisation of the iron, akin to the processes of carburisation of wrought iron described by travellers in South India such as Buchanan. The ingot when retrieved from the cooled crucible would resemble the cakes of wootz steel. Then the ingot was heated by them in a gas-fired furnace to minimize the formation of oxide scale during forging. At least about 50 cycles of heating and forging, known as annealing, seem to have been needed in a fairly labour intensive process. The decarburised surface was removed by Pendray using an electric belt grinder. For the 'Mohammed's Ladder' effect of a ladder-like pattern on the blades, grooves and drill holes were cut into the surface of the blade and the blade was again forged and the surface polished. The surface of the blade was then etched in acid to bring out the wavy pattern where the softer steel phases appear dark and the carbon-rich harder steel phases appear as bright lines.

But what are these patterns of 'kirk and rose' and 'Mohammed's ladder', and how were they formed? The famed pattern known as the Mohammed's ladder which is said to have been found on many Damascus blades such as the Persian Samshir, also known as 'kirk and rose pattern' or ladder and rose pattern, is one which blacksmiths attempting to forge Damascus blades have particularly followed with ardour (Figure 40). This 'ladder and rose' pattern consisted of a series of ladder-like lines, with a central flowery pattern. The belief was that such a sword would enable the Muslim fighter to ascend to heaven. John Verhoeven wrote in the Scientific American on 'The Mystery of Damascus Blades' in 2001 about one method to recreate the fabled 'ladder and rose' pattern:

"Our re-creation of the Damascus blade helps us to answer another question: How did the ancient smiths generate the Mohammed's ladder pattern? Our work supports one theory proposed in the past - that the ladder rings were produced by cutting grooves across the blades. The ladder pattern was made by incising small trenches into the blade after it had been forged to near its final thickness, then subsequently forging it to fill in the trenches. Such forging reduces the spacing between light and dark bands on the final surface especially along the edges of the trenches. The round configuration between the rungs known as the rose pattern is also known from old scimitars. It comes from shallow holes frilled in the blade at the same time the grooves were cut".

One only has to surf the web to realise, that even today, the enigmatic art of forging Damascus blades has captured the imagination of numerous scholars and blacksmiths the world, and has acquired quite a cult following. Ric Fuller is another committed American bladesmith who has been working on making Damascus blades from wootz ingots. He states on his website that to his knowledge he is the only person who has created wootz by both traditional as well as modern methods.

Of all oriental and Damascus blades, the most fabled of all is the Persian Shamshir. This blade is thought to have been made of wootz steel, which was especially famous for its 'kirk and rose' or 'ladder and rose' pattern. The Indian talwar is in some ways equivalent and there are also several Indian examples of watered Damascus blades. Ric Fuller has been able to make reconstructions of the Persian Shamshir from wootz steel with the famed ‘kirk and rose’ pattern on the blade. He also demonstrated the making of Damascus blades at an exhibition in 2002 of the Smithsonian Institution Folk Life Festival on the Silk Road to show the various types of weapons that were made or traded along the route. The Annual Smithsonian Institution Folklife is an annual picturesque and lively event that takes place on the mall next to the Smithsonian Institution opposite the imposing Capitol Hill. Figure 41 is a picture of Ric Fuller forging blades at the Smithsonian Festival.

The following excerpt gives an insight into how Ric Fuller got interested in blacksmithy and wootz steel following interests in karate and martial arts which would especially make enjoyable and inspirational reading for young students of metallurgy in India so that they should not look down on blacksmithy as a ‘lowly’ profession associated with rural artisans:

“My interest in weaponry began when I was young and learning Shorin-ryu Karate. To be honest I had no skill at the martial arts, but it laid the seed for my future studies. In college I studied History and History of Technology with an emphasis on ancient and medieval metal working practices. From those studies I began to view cutting tools in their historical perspective but never quite loosing the mystery and excitement of my dojo days. Slowly, while attending college I began to learn and practice blacksmithing under the guiding hammer of Paul Marx.

In my current body of work I seek to make essentially two types of blades -- historical reconstructions and modern creations. I have a deep respect for and interest in the work of those who have come before and have been systematically recreating certain techniques of steel manufacture. Among these are the smelting of iron ores, carborization of iron, smelting of various crucible steels and the rediscovery of wootz steel. My modern creations revolve around the manipulation of steel chemistry and patterns in new and beautiful directions. I have a good base of knowledge surrounding "Damascus" steel - both pattern-welded and Indo/Persian wootz crucible steel. My wootz studies have been ongoing since 1992 and to my knowledge I am the only person who has created wootz by both traditional as well as modern methods. I guess the end result is that I have been developing the skills and techniques to make the cutlery I find interesting whether that be a Persian Shamshir in wootz with the famed "kirk and rose pattern on the blade or a Norwegian laminated blade for your next hunting trip…”

Chapter 8:

On Pattern-welded Damascus Blades: Imitation as the Best Form of Flattery

"I have forged many a weapon in my life",
said the old man. "Yet not of steel, but of
malice and cunning. The wounds which they open
still allow me no rest. This is why I offer help
wherever it is needed. Let me help you! Trust me,
I also forge weapons just and true, whether they have
blades from Solingen or Damascus!"

-Tale from Solingen, after Manfred Sachse, 'Damascus Steel', 1989

Introduction to Pattern-welding

The deliberately pattern-welded blades, which have sometimes been mistaken for true patterned Damascus blades, have been made in parts of the Far East, such as Korea, China, Japan, Indonesia as well as many parts of Europe. Even though it is not so well known, pattern-welded Damask steel was also used in India to make firearm barrels and sword blades. Whether the evolution of these blades in Europe and Asia followed individual paths or whether there was a mutual influence due to trade and travel is still under study. In these pattern-welded Damascus blades, a damascene-like effect is achieved with a pattern of alternating dark and light wavy stripes by alternately forging strips of low and high carbon steel. However, these patterns are generally much larger and more easily visible to the eye than the fine patterns of Damascus blades.

Interesting types of welded or laminated iron and steels were also made around the world. Such sandwich-like laminated blades could have served three purposes. Firstly, the repeated folding over and hammering of wrought iron could squeeze out the slag and improve the purity of iron. Secondly, in many places steel itself was very rare since only thin layers of low carbon steel could be obtained by carburising iron by heating it in charcoal fire. In these layers of steel, layers of wrought iron could be folded and forged to make a bulkier artefact. Thirdly, and no less significantly, the process of laminating could also give a distinctive and aesthetically appealing pattern, putting a unique stamp like a signature on the artefact.

Sometimes different grades of iron and steel were combined in a variety of ways to compensate for the scarcity of quality steel leading to pattern-welding. These used the harder steel at the edge and softer lower carbon steel or iron in the central portions for cushioning the blows. Pattern-welding consisted of the folding or twisting of layers of steel into a finely laminated structure.

It may be added that these products represent composites, which take advantage of the presence of disparate materials. The Egyptian bricks, containing clay and straw, are often quoted as some of the early examples of composites. The introduction of a design in the geometry of the two materials of the composite makes for a revolutionary change. While the pattern-welded swords are a fine example, there are other earlier references. Thus, Homer describes the shield of Achilles in the Iliad, composed in 800 BC. The shield was made of five layers with a sequential arrangement of bronze, tin, gold, tin and bronze. In modern parlance this will qualify as a functionally graded composite!

Pattern-welding in European tradition

Pattern-welding has been detected in the swords of the Romans, the Celts and in those of the Vikings, and the Merovingians in the Rhine river area. The Vikings and the Merovingian Franks were the first to develop and master pattern-welding techniques. Blacksmiths in these areas discovered that the strength of the blade was increased if the steel layers were twisted. This discovery led to the development of elaborate patterns. Pattern welding exploits the different responses of steels of varying carbon content to acid etching. Upon etching, pure iron appears white and steels appear brown or black.

Although this technique created beautiful designs on the blade, it seems to have died out around the tenth century. This was due, at least in part, to the weakening of the blade that resulted from the extensive welding required to make the patterns. Blacksmiths went back to making stronger blades with the more simple, layer-welded method. Western interest in pattern-welded blades rose again during the Crusades of the 12th, 13th, and 14th centuries. The Damascus blades captured the interest of the crusaders. Many weapons, with their distinctive and beautiful patterns, were brought back as souvenirs. Western blacksmiths were unable to duplicate the distinctive wootz steel patterns but began again to produce pattern-welded Damascus blades as an alternative.

The desired pattern is created by stock removal, punching, or twisting the laminate. The pattern produced depends on the manipulation of the laminate. Stock removal can produce a wavy pattern by causing distortions where steel has been removed. Punching covers the surface with indentations of specific designs that are revealed upon polishing and etching. Twisting the laminate creates a patterned bar which can be ground, filed or re-forged.

Toledo Swords of Spain

Toledo is a city in Spain that rivalled Damascus in terms of the quality of the swords it produced. As Spain was a meeting ground for Christian Europe and the Islamic Moors, special interest is attached to this development. In time the Toledo process led to the famous rapiers made popular by the fictional exploits of D’Artagnan and the celebrated three musketeers in France. The fame of the Spanish Toledo process was such that when there was interaction between the Japanese and the Spaniards, the former came to Toledo to have their ‘katana’ and ‘wakizashi’ swords forged there.

Kris from Indonesia

A fascinating Asian example of a welded or laminated steel is the *kris* from Indonesia and Malaysia which quite literally also had a ‘heavenly’ touch. These seem to have been made by laminating two grades of low-carbon steels and in fact some of the layers also contained iron from the heavens, i.e. meteoritic iron which contained about 5-7% Ni. This nickel-rich meteoric iron layer gave a beautiful silvery pattern against the dark background of steel, making the ‘kris’ an exotic example of a deliberately patterned artefact (Figure 42). These swords had a sinuous form.

Japanese Samurai Swords

Japanese swords have been highly acclaimed for their beautiful patterns owing to lamination techniques of different grades of iron and steel resulting in visible heterogeneities and aesthetic patterns. Cyril Stanley Smith effusively wrote that ‘the best of all examples of a satisfactory art form based upon the inner nature of a metal is provided by Japanese swords’. The Japanese swords were often made by repeated forging, welding and reforging of the sponge, alternate layers of high carbon and lower carbon steel as many as 20 times which could as many as 2^{20} layers of metal This would result in a visible texture because the slag inherent to the metal would resist deformation in a different way from the ferrous regions, giving an interesting gradient in the metallurgical texture. This would be aesthetically highlighted by the minimalistic shaping of the sword. Figure 43 illustrates the many steps involved in the creation of the sword. Edgar C Bain is celebrated for his discovery of the constituent in steel named after him as ‘bainite’. He was an ardent admirer of Nippon-to, as the Japanese sword is called. He has recorded that the Japanese sword is so admired that numerous swords were brought to the USA by the returning members of the occupation forces after the Second World War, and there are possibly more Japanese swords in the USA than in Japan!

Two basic types of multiplate construction are demonstrated in the structure of many traditional Japanese blades. The first type is creating a hard steel jacket around a softer core (kobuse san mai kitae). The second type places the hard steel between softer steel side plates and /or back (hon sai mai kitae). Both of these techniques were transplanted from the Chinese mainland, where they had been in use as early as during the Bronze Age. Trade along the Silk Road spread sword making influences in different directions In medieval Japan the Samurai wore two swords—a longer sword known as a ‘katana’ and a shorter sword called a ‘wakizashi’. The wakizashi remained beside the Samurai whenever he was indoors—when he ate, slept or bathed. The shorter length facilitated fighting in close quarters and low ceiling heights. In the late 19th century, the Samurai order was disbanded. However, the Japanese sword which had been hailed as the "Soul of the Samurai" still remains a very important part of the identity and soul of the Japanese people (Figure 44). .

Although Japanese sword making goes back to the Bronze-Iron Age and fine blades were made during the peaceful early Heian Period, it was the Kamakura era (1185-1392), the heyday of the aristocratic warrior that saw the Japanese sword reach a level of perfection never matched elsewhere, not even in the finest forges of Islamic Spain. Even the imperious Chinese recognized the surpassing excellence of the swordsmiths of the east. “Treasure swords of Japan,” says a Sung Dynasty poem, “are got from the East by merchants of Yueh, who wears such a sword which can slay the barbarians.” It was higher praise than the Sung poet knew, for sword making was, of all crafts, most intimately involved with the native cult of Shintoism. The sword maker was a priest who obeyed rules of abstinence and sexual continence when bringing an icy blade out of the fiery forge.

The key to the greatness of Japanese blades was the very painstaking and time-consuming process. A bar of iron was welded lengthwise to two bars of different grades of steel; this triplex was folded upon itself and hammered out again to its original length. The metal was coated with a clay–stew ash mixture, fired, folded again, coated, fired and so on. The fifteen or twenty doublings and hammerings that were usual in the smithing process produced thousands of layers of steel. When, as sometimes was the case, the smith began with three or four separate triplexes, welded them and then folded them five times, the sword could contain some four million microscopic steel strata.

Tempering of the edge was both an art and a science and sword-making schools differed primarily on the questions of how long to heat and how long to cool the edges of the blades. To call the edge of the Japanese sword razor sharp is to do it little justice. The finest Japanese swords could gently slice through a square of silk dropped out of the air onto their upturned edges.

The swords represent at some level the ethos of Japan. It is one of the three precious objects handed down the Japanese imperial family. Many swords had inscribed on them the names of the swordsmiths, Buddhist prayers and in early years even characters in Sanskrit. Occasionally the name of the swordmaker was left out, as the master bladesmith was so sure of his artsistry that he felt that his work spoke for itself. When a sword had to be tested, it was often done against human bodies indicating how many bodies it cut through (Figure 45).

Parts of a Japanese Sword

A tsuba is the hand guard of a Japanese sword. Its original purpose was to protect the hand of the wielder of the sword from an attack by his adversary. It also prevented the hand from gliding into the blade. During the tumultuous Muromachi period (1333-1573) and the Momoyama period (1573-1603) these were its main purposes. However, the Edo period brought uninterrupted peace from 1603 to 1868. With relative calm, the tsuba turned into an object of art. Generally, iron was used for making a tsuba. With growing refinement, a wide variety of metals-copper, bronze, silver and gold-were used. Their shapes can be simple ranging from a plain circle to an ellipse or more complex. decorations which were inspired by religion, history and mythology. Often, dragons or natural forms like leaves formed the motifs. Figure 46 shows some typical tsubas.

Mokume Gane –a Japanese product- is of relatively recent origin. ‘Mokume’ literally means wood eye and ‘gane’ means metal. It refers to the visual appearance of the pattern in metal approximating that of wood. It forms an interesting contrast with the Damask texture discussed earlier. It was mainly in vogue from the late sixteenth century to the middle of the nineteenth century. Feudal Japan was obsessed with swords and their decorations. The mokume gane technique is attributed to Denbei Shoami (1651-1728), a master smith from Akita prefecture. He combined copper with 'shakudo', an alloy of copper with 4% gold, in the form of a laminate to create a form similar to Chinese and Japanes lacquer work. Several 'tsubas' have this type of origin. Roberts–Austen, of the Fe-C diagram fame, was fascinated by the 'mokume gane'. There was one description, where there was a mistaken reference to soldering various layers together for creating mokume gane. This led to failures by those who subsequently tried to recreate it, as delamination occurred at the solder joint.

Japan gradually abandoned this product. In the early part of the twentieth century interest in the west in these matters also waned. Again, it was the intervention of C S Smith that led to a revival of this subject. There are now more people in the USA working on mokume gane than there ever were in Japan! Essentially, solid state diffusion is the key to processing dissimilar metals to come together. Careful temperature control can be exercised in the modern experiments.. Thus the ancient process has arisen, phoenix-like, leading to a variety of laminates involving copper, gold, iron, palladium, platinum and silver (Figure 47).

Indian-made Pattern-welded Damascus blades

G.N. Pant, of National Museum, New Delhi has written a seminal book on 'Indian Arms and Armour'. As reported by him amd Manfred Sachse in his book on Damascus steel there are also several Indian examples of pattern-welded damask steel. One popular use was in firearm barrels to give them an attractive texture. There are Indian and Afghan examples of firearm and matchlock barrels with damask ribbons running clockwise and counter-clockwise or with 'chevron' and mosaic patterns. Furthermore, some of the Indian talwar blades were also made of pattern-welded Damascus steel with elegant patterns to beautify them. Sachse was introduced in 1981 to a maker of welded Damascus blades, Gopilal, in Rajasthan through Pant. At the workshop of Gopilal three men were needed for the forging, viz. the smith, hammerman and bellows operator. Occasionally women could also help in the hammerwork. Sachse reports that it was 'an unforgettable experience' to watch the manufacture of welded damask blades in a remote Indian village, working until the moon rose and with no electricity. The blades were made by repeatedly folding over and forging together hard and soft iron or steel plates. This was a technique, which was basically similar to that used elsewhere in Europe, Japan or Indonesia.

Pattern-welding by Modern Bladesmiths

Even though superior weapons have displaced the swords from battles and wars, the symbolic value of the sword can hardly be exaggerated. It combines both form and function as well as utility and beauty as no other product does and holds mankind in its thrall. Academics and bladesmiths collaborate to produce a variety of patterns. Societies, clubs and guilds are active across USA, Europe and Japan.

There is a major following for the making of pattern-welded blades amongst modern blacksmiths and bladesmiths. It has been elevated to an art form that also utilizes modern technology. For example, the American bladesmith Ric Fuller, makes complex mosaic steels using pattern welding, and also makes the more conventional range of twisted, random and ladder patterns.

Sachse, who has made some of the most extensive studies on true and welded Damask steel and pattern-welded blades, has also drawn inspiration from the famous pattern-welded blade making centre of Solingen in West Germany. In fact, this chapter opens with a quote of an anecdotal tale of an old bladesmith from Solingen wherein the man pleads the case that his work is just and true whether he makes the true Damascus blade or the false pattern-welded Solingen blade which imitated the Damascus blades! Sachse made a replica of a pattern-welded forging of a fine late 18th century pattern-welded Damask blade from Europe including the signature ‘DAMASCO’, and all its rosettes and wood grain-like appearance. Figure 48 shows a fine example of the mastery of pattern-welding by Sachse.

Nihon Bijutsu Token Hozon Kyokai (The Society for the Preservation of Japanese Art Swords- NBTHK) was founded in February 1948 by the Japanese government in order to save Japanese sword that was in a critical situation of total destruction when the occupation forces tried to confiscate all the Japanese swords from Japanese people just after World War II. It has many branches in Europe and the USA. It brings out a journal. The "International Society for Damascus Steel Research" (Internationalen Gesellschaft für Damaszenerstahlforschung) was established in 1995 at the Freilicht Museum in Germany with "Damascus smith" Manfred Sachse of Mönchengladbach, as its President. The Order of the Damask was founded by Sherby and Wadsworth on September 16, 1997, to promote the understanding and application of ultrahigh-carbon steels, Damascus steels, their laminates, and superplasticity in these materials. It is to be hoped that India, which gifted the wootz steel to the world, will see a similar surge of enthusiasm.

The film industry today nurtures this field as well. History, fantasy and science fiction films draw upon swordplay. Martial tradition of the East and the West are celebrated in these films. Just as paintings are collected, quality swords are collected by connoisseurs. Prices may go up to several lakhs. Attention has already been drawn to the fabulous price commanded by Tipu’s sword.

Patents and Industry

Even though wootz steel or ultra-high carbon steel in modern terms is an Indian invention, modern research on simulating ultra-high carbon steel has sought protection in intellectual property rights. There are other ironic instances where prior Indian discoveries such as Neem and Basmati have emerged as patents in the West! Verhoeven and Pendray filed a US patent for a method of making Damascus blades in January 1992.

Only recently, however, the Indian government has been waking up to the need for patent protection and some traditional crafts are being patent-protected through a Geographical Indication tag such as an exotic metal mirror making craft from Kerala.

Modern industry has taken some interest in Damascus blades. In November 1992 a co-operation began between Söderfors Powder AB and Kaj Embretsen, Bladesmith, Edsbyn Sweden. A successful method to produce patterned material by use of powder metallurgy (PM) was developed during 1993. A new company, Damasteel AB, was formed in August 1995, to serve the market with Damascene steel billets and bars. A patent was awarded in June 1996 regarding methods to produce patterned billets from PM. Angel Sword Company is marketing Techno-wootz Damascus Steel under their trademark. Heimo Roselli, a Finnish knifemaker, is making Damascus knives for sale.

Laminated Composites

Wadsworth has considered ancient laminated composites in detail. Table 6 is adapted from his paper and helps gain a proper perspective over pattern-welded swords.

Table 6 Examples of Ancient Laminated Composites

Material	Period	Layer 1	Layer 2
Gizeh Pyramid plate	275 BC	0.2% C	Wrought iron
Chinese blade “Hundred Refinings”	AD 100	Negligible	Low Carbon
Merovingien blade	2nd-12th Century AD	Carbon steel	Pure iron
Japanese Sword	400 AD to present	1.0% C	0.2% C
Indonesian kris	14th century AD	1.0 % C	Meteoric Fe (Low C)
Chinese pattern welded blade	17th Century AD	unknown	unknown

When two materials are mixed, the resultant properties are between those of the constituent materials. This is called the rule of mixtures. It is intriguing to note that toughness in a laminated composite is often superior to that of either of the constituents. Inspired by the pattern-welded swords, Sherby and Wadsworth made laminated composite with 12 layers of UHCS and mild steel. As Figure 49 demonstrates, the laminate shows superior toughness in comparison with mild steel and UHCS.

Chapter 9

Archaeometallurgy of Wootz: A Beginning without an End

‘There in the very middle
Of battle-camps
that heaved like the seas,
pointing at the enemy
the tongues of lances,
new-forged and whetted,
urging soldiers forward
with himself at the head
in a skirmish of arrow and spear,
cleaving through
an oncoming wave of foes,
forcing a clearing,
he had fallen in that space
between armies…’

Poetess Auvaiyar (Tamil, Purananaru 295, ca 100 BC
(translated by A.K. Ramanujan, 1985)

The Road to Mel-siruvalur

“It was back in 1991. I am on a madcap mission-as only a motivated Ph.D. student can be- to track down every last trace of copper mining and metallurgical activity in ancient South India and every last old mine shaft there is.

The exuberantly carved temple tower at Tiruvannamalai in Tamil Nadu looms overhead. ‘So… Polama? (i.e. shall we go?)’, I say optimistically in my city-accented Tamil to my companions for the day. They include an obliging local reporter for the Dinamalar newspaper and a swarthy driver of an auto-rickshaw, who looks at me again in a perplexed and disbelieving fashion. We are to set off to find Mel-siruvalur, which local hearsay suggests might just be a lucky hunting ground for a budding archaeometallurgist on the prowl. And so we lunge into the unknown, down a long and winding road through an arid and de-populated scrubland.

Fifty kilometers or something did they say? More like a hundred and fifty. The bump and grind of the auto ride gets progressively bumpier. It becomes apparent that one is looking for a needle in the haystack. Just as we have had enough, we make that last ditch effort and ask the next villager one last time, ‘OK, this Mel-siruvalur, how much further is it?’ He points his thumb dismissively to a clump of houses behind him, ‘inge (i.e. here)’. We stagger unsteadily into a one bullock-cart, 2-house village. ‘Now then’, I say with desperation, ‘I am looking for something Old? bits of pottery…?…somebody from the Geological Survey in Madras said something about old mining sites…?’. ‘Ah’, said a *villager, 'the PWD or somebody was digging near a canal and found old pots, down that way'. And so it transpires that I come across this mound. It catches my attention because of two cows grazing, the picture of bovine contentment. I stop to take a picture of this Eternal Rural India. Just then I notice the stuff lying around on the mound. 'What's all that,is it not fossilized cow-dung?'. My mind flashes back to one of our enthusiastic lecturers at the Archaeology Institute in London, waving a piece of smelted debris at us and saying 'you see, slag has this nice flow texture'. 'So, that's what it must be', I re-assure myself as I pick through the dried cowdung and scoop up bits of lava-like stuff, broken 'pot-sherds' and such like.*

A couple of years later, I am in the laboratory of the Institute of Archaeology, London. I finally get down to looking at that 'copper slag' from the back of beyond. I pick a 'pot-sherd' and I grind, scrape, polish and then peer at it under the microscope. Serendipity? I see something, something globular, bright and steel-grey! It couldn't be! But it is, it's a prill, or a metallic globule of Steel! Stuck inside a CRUCIBLE! I've found evidence for CRUCIBLE STEEL! Yes, it is that high-carbon WOOTZ STEEL, isn't it, seen in the honeycomb-like micro-structure resembling the published micro-structures of patented ultra-high carbon steels of about 1.5% carbon! One can see too where that legendary mixture of soft steel and hard steel that resulted in the beautiful light and dark wavy etched 'Damask' patterns came from: right there in the etched metallic structure showing a matrix of dark pearlite, the soft steel, being surrounded by a honeycomb network of light, higher carbon cementite, the hard steel. So, they were making those 'CAKES of STEEL' in crucibles after all! Am I staring at the archaeometallurgical discovery of a lifetime, or what? And all thanks to two cows! Hurray!"

My mind throbs with haunting nostalgia of a conversation I had with Nigel Seeley, one of my tutors in the post-graduate research in archaeometallurgy. Just before I set off with trepidation and anxiety to India from London in 1990 on my proposed fieldwork towards my Ph.D. in archaeometallurgy, Seeley had boosted my morale with the words: 'You are going to find things, which will be revelationary.'.

But who on earth was responsible for that precious mound of debris from the smelting of steel in crucibles, in fact, of high-carbon wootz steel? Mel-siruvalur was more a hutment than a village, with nothing in sght for miles together except scrubland; no temple, no tank, no fortification, not even a little wayside shrine below a peepul tree, no clues as to why and for whom it should have been producing high-grade steel at all in antiquity. Mel-siruvalur in South Arcot district in Tamil Nadu was not even part of the circuit of South Indian steel making centres that late medieval European travellers wrote so vividly about of Salem, Mysore, Konasumadram and Golconda. All one could see was that a canal with curious large potsherds stacked all around, some looking strangely like the broken legs of megalithic sarcophagi. In fact there have been mentions of some megalithic sites around there… Could it really be? My imagination gets the better of the archaeologist in me…

Poetess Auvaiyar was one of the authors of that remarkable, enigmatic anthology of classic Tamil poetry described as 'Sangam' poetry. The Sangam era might well have *overlapped with the latter part of the megalithic period. Auvaiyar composed this verse to the warrior Anci in the anthology, the Purananuru, made accessible to a wider audience by the stirring English translations of A. K. Ramanujan:*

…Anci, man of many spears
is at battle.
And as he sets fire,
To enemy camps,
Black battle-smoke,
Swirls around his young elephants
Like mists
around mountain peaks…

Could it be that somewhere here, near little non-descript Mel-siruvalur, was the scene of such a battleground, where rival 'vel' chieftains of the Tamil Sangam era such as Anci crossed their spears that may have been honed to perfection from steel made in little crucibles such as those strewn around Mel-siruvalur? Their skirmishes lost in the mists of the surrounding mountain peaks are now lost to the mists of time… And who was this Auvaiyar who wrote her terse and moving elegies of the 'puram' genre of bardic Sangam poetry: with the immediacy of one witnessing poignant battle scenes; were they dedicated to her own, beloved…? Or is that more fanciful imagination at work, was she rather more prosaic, wizened and wise, like how a school textbook described her: 'a very old lady, the Grand Old Lady of Tamil?'

-Sharada Srinivasan
The Travels and Travails of an Archaeometallurgist (to be published)

Studies on Crucible Steel in Asia

A clear understanding of the antiquity of wootz steel making in India suffers from the fact that systematic archaeometallurgical studies have not yet been mounted. However, there is a considerable body of circumstantial evidence in the archaeological record which suggests that crucible steel making originated in India before spreading to other parts of Asia. There is promising preliminary evidence from iron age and megalithic horizons in peninsular India from mid 5th millennium BC to early centuries AD for the production of crucible steel. Traditionally, as known from travellers' accounts of Voysey, Buchanan, Holland and others, wootz steel was being made at several locations in the Salem district of Tamil Nadu, in Mysore and Chitradurga districts of Karnataka and the region in Andhra Pradesh north of Hyderabad and south of the Godavari River.

One of the earliest Indians to have played a pioneering role in reviving interest in traditional Indian crucible steel was K. N. P. Rao with the Indian Institute of World Culture, Bangalore. The scholar to have undertaken the most comprehensive and painstaking archaeometallurgical investigations on processes of manufacture of wootz steel from field investigations has been Thelma Larson Lowe from the University of California, Berkeley. To these studies on South Indian wootz, one may add some sites newly identified, quite by chance, by Sharada Srinivasan, during field surveys for copper mining or smelting.

The scope of archaeometallurgical studies in iron and steel heritage has been demonstrated in recent times from other parts of Asia. Spectacular archaeological studies comprising concerted excavation and archaeometallurgical investigations on material from Central Asia by a team of scholars from the Institute of Archaeology, London, and from Sri Lanka by Gillian Juleff have yielded evidence that they were important centres of ferrous metallurgy and crucible steel making before the10th century AD. As a result, in recent times the spotlight has been effectively turned away from India in these respects. It may be noted, however, that all crucible steel need not have been high-carbon steel nor have produced the banded Damascus patterns.

Figure 50 shows a map of India indicating some of the sites discussed in this chapter. In a way reminiscent of Buchanan’s journey through the countries in South India, the following sections describe the investigations carried out in Tamil Nadu (Kodumanal, Adichanallur, Mel-siruvalur), Karnataka (Gattihosahalli, Tintini, Machnur) and Andhra Pradesh (Konasamudram). It appears that while there was some similarity in the production of crucible steeel, there were also differences. Only in a few cases excavations have been carried out unearthing old furnaces. Many investigations relate to surface finds of furnaces and crucibles of the nineteenth century. A reference to the novel wind-powered furnace in Mawalgah in the neighbouring Sri Lanka will be made. Finally the recent insights obtained about crucible making in Central Asia (Merv in Turkmenistan nad Achsiket in Usbekistan) will be highlighted. The descriptions are not exhaustive but are meant to convey the flavour of archaeometallurgy.

Wootz from Tamil Nadu

One of the earliest known sites, which shows some promising preliminary evidence that may be linked to ferrous crucible processes is Kodumanal, near Coimbatore in Tamil Nadu. Excavations were undertaken by K. Rajan, Tamil University, Tanjavur uncovered a substantial megalithic-burial-cum habitation site dating back to the 3rd century BC. Interestingly, this site has yielded evidence for the production of semi-precious stone beads and cotton textiles and was part of a long distance exchange network reaching the Red Sea and Egypt as pointed out by Peter Frances from the finds of beads. A set of thirteen furnaces was uncovered. Inside one of the smaller furnaces a vitrified crucible fragment was found, although lid fragments were not identified. Since the slag and debris were related to iron smelting, it is relevant to speculate if the crucibles were related to crucible steel production.

Metallographic investigations were undertaken on one of the crucible fragments from Kodumanal by Sharada Srinivasan. The specimen examined is indicated in Figure 51 along with an assemblage of other debris related to iron smelting, which shows that it formed the vitrified base of a fired crucible. The shape and fabric of the crucible was not dissimilar to the carbonaceous crucibles found in Southern India related to crucible steel production. Scanning electron microscopy and electron probe analysis did not indicate significant amounts of any other non-ferrous metal like copper, gold or silver, whereas some iron-rich constituents with at least 70% iron were found in the crucible fabric. This left open the possibility that the crucible was related to some ferrous process such as the refining or carburisation of iron akin to the wootz process. Furthermore, one of the ferrous metal pieces excavated at Kodumanal was found to have a high-carbon steel edge. In useful surveys by Arun Kumar Biswas on Indian iron and steel and by Paul Craddock on crucible steel in Asia they also maintained that the pre-Christian Tamil region could have been a potential early centre for the emergence of crucible steel.

The Roman accounts of 'Iron from the Seres' also take on significance in this context because Tamil Sangam literature refers to the Tamil Chera dynasty with sites such as Kodumanal falling into this timeline and geographical sphere, while it also shows evidence of being part of long distance exchange networks.

B. Sasisekaran, University of Madras has pointed out in a survey on ancient Tamil Nadu that skilled iron smelting techniques had emerged by the megalithic period around 500 BC with some of the largest furnaces then found from the Indian subcontinent. The promise that more concerted studies on south Indian pre-history may hold out is borne out by recent exciting excavations that have been undertaken at Adichanallur in Tamil Nadu indicating that it was an extensive iron age and megalithic urn burial site going back to about 1000 BC with finds of Tamil Brahmi graffitti on potsherds ranking amongst the earliest known evidence of writing in South Asia. As for religious affiliations, the local Hindu war-god, Murugan, with the trident, seems to have been most popular in the Sangam era.

The possibility of a link between the term 'ekku' of Tamil Sangam poetry and 'ukku' and the preliminary findings from Mel-siruvalur in Tamil Nadu of wootz crucible steel and of nearby remains from megalithic occupation inspired the bit of imaginative narrative outlined in the piece 'The Road to Mel-siruvalur'. This is well captured in Figure 52. The Tamil Sangam era is thought to have coincided to some extent with the megalithic period. The illustration depicts Auvaiyar, Tamil poetess of the Sangam era, looking on and holding the traditional writer's palm leaf manuscript, as chieftains such as Anci, 'man of many spears' engage in tumultuous battle in the background, while some artisans work overtime to make crucible steel to be turned into spears!

Iron ore is found in parts of Tiruvannamalai taluk in South Arcot district in Tamil Nadu. The village of Mel-iruvalur is located 8km south of Moongilthuraipettai in Sankarapuram taluk in South Arcot. In 1991, Sharada Srinivasan came across unreported dumps, debris and trenches near of Mel-siruvalur. One of the trenches showed evidence for bloomery iron smelting, while evidence for crucible steel production was found at a nearby dump as mentioned later in this chapter. In an adjacent canal, some trenches were dug up exposing several potsherds, some which looked like megalithic storage jars. The debris from crucible steel production of broken crucibles and bits of slag were found not only on the dump but were scattered all the way around the perimetre of the area and into the canal area. The phenomena of rains and winds would have scattered the crucible debris widely around.

At the dump or mound thousands of broken crucible fragments were strewn all around. Pieces were retrieved constituting the base, middle and top portions of crucibles, an assemblage of which is indicated in Figure 53. These seemed to have formed parts of closed aubergine-shaped crucibles where the ingot is formed at the base of the crucible of a diametre of about 7cm. The thickness of the walls ranged between 1-2cm. The crucibles would have been fired once with the charge and then broken to retrieve the ingot.

Cross-sections of various fragments of the crucibles were randomly made, including the inner lining of the crucible, which had rusty metallic remnants, and a lid fragment. Trapped in the glassy matrix of the vitrified crucible fragments were found a few metallic globules ranging in size from 10-100 microns. The metallic structure of some of these globules was striking. The microstructure (Figure 54) corresponds very well with the structure of high-carbon steel of about 1.3-1.5% carbon, indicated by the honeycomb network indicating prior austenite grains of light-coloured cementite phase surrounding the inner darker lamaellar pearlite. Scanning electron microscopy and electron probe microanalysis confirmed that the globule was ferrous and helped to identify the phases. It may be noted that the microstructures of ultra-high carbon steels of about 1.5% carbon simulated by Sherby and his colleagues. They had forged to show that they were comparable in the end structure to worked Damascus blades. Thus, it is reasonable to envisage that the ingots produced through the crucible steel process at Mel-siruvalur could have eventually been turned into the watered Damascus blades.

At Mel-siruvalur, the process of making high-carbon steel seems to have been one where wrought iron was carburised to high-carbon steel by packing it inside crucibles with carbonaceous materials and firing it over long firing cycles. This is suggested not only by the finds of bloomery iron near the site, but also by the highly carbonaceous crucible fabric and the fact that the inner portions of some of the lids had markings that suggested they could have been packed with stems, leaves, grass or such organic matter. It may be noted that Buchanan in one of his accounts of crucible steel making observed in the Mysore region had mentioned a firing cycle of at least 12-14 hours. Furthermore, the globular nature of the metallic remnants trapped in the crucible suggested that the charge had reached something close to a molten state.

Mysore Process

If one were to name one site, which has been written about more than any other in recent times in connection with crucible steel production in South India, it is Gattihosahalli (new steel village in Kannada) in Chitradurga district of Karnataka where production was recorded at the end of the 19th century. Rao undertook extensive explorations of this site of the nineteenth century. Reference must also be made to archaeometallurgical investigations on crucibles from this site by Martha Goodway of the Smithsonian Institution, who undertook important re-firing experiments on the crucibles. Paul Craddock of the British Museum has also added to our knowledge about this site. Figure 55 shows crucibles from the collection of Rao. At Gatihosahalli, the method of making crucible steel seems to have been the carburisation of wrought iron to steel by packing it with carbonaceous materials. This has earned the nickname the ‘Mysore process’ after Buchanan’s accounts.

Sharada Srinivasan has uncovered evidence for crucible steel smelting from the site of Machnur and Tintini, near the banks of the Krishna River in Raichur district of Karantaka. These crucibles were similar in fabric to those from Mel-siruvalur in being highly vitrified and glazed with the darkish matrix suggesting they were carbon-rich. The carbonaceous matrix suggested that in these crucibles too, the process to make crucible steel may have been the carburisation of wrought iron. Sharada Srinivasan and Dafydd Griffiths have made comparisons were made between crucibles from these various sites with those from Gatihosahalli which all seemed to have a carbon-rich fabric. However, what was also striking was the fact that in comparison with crucibles and debris from the fairly recent site of Gatihosahalli, those from the sites of Mel-siruvalur, Tintini and Machnur were far more weathered and worn out, raising the possibility that they represented much older crucible steel production activities.

Investigations on Deccani Wootz

The evidence from Kodumanal is not the only potential indicator for the production of crucible steel from megalithic contexts. In another preliminary finding, A. Sundara pointed to the report of a sample with 1.7% carbon from a megalithic site in Andhra Pradesh of the pre-Christian era, which is comparable to the composition of wootz steel.

Thelma Lowe’s remarkable and extensive surveys in the region of Andhra Pradesh resulted in the identification of many as fifteen sites for crucible steel production in the area of Konasamudram and Nizamabad in modern day Andhra Pradesh. She began her research working in the archives of the Dutch East India Company in the The Hague, Netherlands, where she explored evidence for trade in wootz ingots from the Deccan. By March 1989 she had doggedly completed an extensive sixteen month field survey of several sites for wootz making and iron smelting sites in the Central Deccan, falling in parts of Andhra Pradesh. In this time she had surveyed an astonishing 6000 square kilometres of area falling between 72 km E-W and 110 km N-S. Within this area she identified, mapped and sampled as many as 94 deposits of iron smelting debris located on 74 production sites. In addition to evidence for wootz crucible steel from fifteen of these sites, she also found evidence for early mining operations at eighteen sites. Although these crucible steel sites have not yet been dated through archaeological excavation, Lowe has pointed that this area traditionally had an iron smelting industry that dated back to the first millennium BC with the smelting of lateritic and magnetite ores that could have supported the Deccani wootz process.

Travellers such as Voysey had written about the manufacture of crucible steel in this area of Konasamudram. Interestingly, Lowe described the area surveyed by her as an ‘industrial park’ marked by extensive activity of something of an industrial nature ranging from concentration of high-quality raw materials, complex smelting skills, procurement and marketing information, populated by skilled iron-makers and industrial organisers in proximity to politically important centres. In this day and age when high-profile ‘Information Technology Parks’ have been springing up in cities such as Bangalore, Hyderabad and Chennai it is interesting to be reminded of the local precedence of semi-industrial complexes for wootz steel.

Lowe undertook landmark studies to understand the nature of the Deccani wootz crucible which was crucially well adapted to the formation of a high-carbon iron alloy. The crucible fabric was found to be sufficiently refractory to not only withstand the long firing cycles under highly reducing conditions but also had necessary insulating properties for the formation of the cast ingot. Thereafter another functional necessity was that the crucible had to brittle enough for the cast ingot to be easily retrieved by breaking the crucible. The charged crucible according to Lowe was fired in long 24 hour firing cycles reaching temparatures of least 1250 ^{0}C. Deccani crucibles had the advantage of being in some ways comparable to modern ‘carbon refractories’ due to the excess of carbonaceous materials in the fabric of the crucible which would have helped the crucible to resist well the attack by molten metal or slag given the highly reducing conditions in the furnace. After firing, the clayey materials in the crucible formed glassy phases. Exciting findings were made by Thelma Lowe together with Gareth Thomas from investigations undertaken at the Lawrence Berkeley Laboratory indicating that the historical Deccani crucible fabric could be characterised in modern terms as a high-performance refractory known as a mullite fiber-reinforced ceramic composite (Figure 56). Such mullite fibre-reinforced ceramic composites are not usually reported in archaeological materials or ordinary refractories and in modern terms consititute a type of advanced high-performance composite material or refractory. Only some porcelains can probably be described as mullite-fibre reinforced ceramic composites. Such mullite fibres would strengthen composite materials.

Crucible Steel and Wind-powered Iron Smelting in Sri Lanka

Recent archaeometallurgical investigations have suggested that Sri Lanka, the emerald isle off the coast of the Indian subcontinent, also supported innovative technologies for iron and steel production in antiquity. It is interesting that Ananda Coomaraswamy, that celebrated doyen of Indian art history, who also had a background as a geologist was one of the early scholars to have taken an interest in crucible steel making. Around 1900 he visited the area of Alutnuvara in Sri Lanka where crucible steel making had recently declined. However, he was able to get two old men to once again demonstrate the crucible steel making process for him. Their method was something similar to the method of carburisation of wrought iron with carbonaceous material of wood or stems as described before in the case of Buchanan’s observations on crucible steel making in the region of Mysore. Excavations were undertaken with the involvement of Gill Juleff at a site in the Knuckles area of Sri Lanka where crucibles similar to those from the Alutnuvara area were found along with pottery which was carbon dated to about the latter part of the first millennium AD, making it a well documented find of crucible steel

In a sensational story demonstrating the significance of experimental archaeology and re-construction experiments, Gill Juleff experimentally showed from the ruins of furnaces in

Sri Lanka that a unique method of wind-powered smelting of iron took place which was a truly remarkable achievement of Sri Lankan antiquity. A series of excavations at Samanelawewa over a 10 km by 10 km area indicated as many as 80 sites with such evidence of furnaces. Juleff has argued that these were powered by strong gusts of wind blowing across this highland area. While this idea of wind-powered smelting had earlier been received with some skepticism by the scholarly community, she went on undertake an exciting series of experimental smelts in replica furnaces to establish that it was indeed possible that iron could have been smelted in such furnaces by taking advantage of prevailing winds. A photograph of her experimental smelt was featured on the cover of Nature in 1996 (Figure 57). This should surely be an inspiration to students to suggest that there is a future in research in materials heritage for the bold and the unconventional. Her experiments also demonstrated that ferrous alloys of the composition of steel could have also been produced in such furnaces. It is not clear, however, if finds of high-carbon steel have been made from Sri Lankan antiquity.

Crucible Steel from Central Asia

Exciting finds have shown that the production of crucible steel was not limited to India or Sri Lanka as previously believed but that places in Central Asia like Merv in Turkmenistan and Achsiket in Uzbekistan which were formerly part of the Soviet Union were important centres of production of crucible steel from the medieval Islamic period. The Merv sites date to the 8th and 9th centuries, while sites in Achsiket date to between the 9th to 14th centuries.

Merv is surely one of the most romantic archaeological sites in the world, located in an oasis in the midst of a high-altitude desert on the roof of the world and lying as it did along the great ancient trading Silk Route that linked China to the Near East: evoking visions of caravanserai loaded with ceramics and silks. The crucibles, described as ‘desert melting pots’, were uncovered when archaeologist Georgina Hermann of the Institute of Archaeology, London began excavating the site in 1992 and went on to win a prestigious Rolex Award for Enterprise for her endeavours. A team consisting of Georgina Hermann, John Merkel, Dafydd Griffiths and Ann Fueurbach undertook research on the archaeometallurgical evidence at Merv for crucible steel. This resulted in the doctoral thesis of Ann Feuerbach. She won a reputed Minerva Award for her efforts.

At the ancient city of Gyuar Kala in the Merv oasis a fascinating and remarkably well-organised crucible steel workshop was excavated which roughly consisted of three well demarcated areas: the area of a sizeable pit containing crucibles in the north of the workshop, an area consisting of furnaces (Figure 58), and an area separated by an east-west running wall. Four furnaces were identified next to an enclosed room adjacent to an open paved courtyard and each of these furnaces was next to secondary structures such as a hut or a protective wall. The well-made crucibles from Merv were in a good state of preservation and seem to be significantly different from the ones from the Indian subcontinent in that they do not seem to have had the carbonaceous elements found in the darker Indian crucibles. Investigations suggested that steel of an intermediate composition is likely to have been made at Merv by melting together low carbon wrought iron with cast iron, as inferred from remnants within the crucibles. This method may be described as a co-fusion process, which has also been observed in parts of Southern India such as the Deccani wootz process. It is interesting to note that Merv was a meeting point in the Silk Road. Knowledge and goods were exchanged. But it had no iron ore, no refractory clay and very little wood for fuel. Thus the steel makers had to be ingenious to maximise the available resources.

Studies stimulated by G. Weisberger, O. Papachristou and T. Rehren have shown that Merv was not the only centre along the Silk Road where crucible steel was being produced. Achsiket in Uzbekistan located in the mineral rich and fertile valley of Ferghana was also a centre for making crucible steel around the 9th-12th centuries until its devastation after the Mongol invasion around 1220. However, whereas the method of co-fusion involving de-carburization of cast iron was postulated in the case of Merv, in the case of Achsiket, it seems to have been tentatively postulated that the process used was the carburization of iron to steel. These sites of Merv and Achsiket lie close to the great cultural and technological centres of Central Asia.

What Survives of Indian Iron and Steel Traditions? A Note on the Agarias

A discussion of ancient Indian iron and steel would not be complete without touching upon the current status of the traditional iron and steel enterprise in India. Today, the skills of making wootz crucible steel are completely lost in India with no traces left behind, apart from the mute debris of crucibles strewn carelessly over many parts of southern India. A few other silent testimonies may survive here and there such as a pair of long tongs still retained by a villager in Gatihosahalli in Karnataka as observed by Paul Craddock. This was used traditionally to haul crucibles out of the furnace.

However, the smelting of iron still thrives in small pockets by tribal communities in central India known as the Agaria. It is useful to touch upon this, just to get some sense by analogy of what the essence of this now dying traditional iron and steel enterprise in India was all about. Rural blacksmithy is still being practised quite widely all over India to make a range of agricultural implements, ploughshares, cooking tools and such like. The Englishman Verrier Elwin, probably India's most pioneering anthropologist, extensively documented the sociological dimensions of this iron smelting community of the Agarias. His book 'The Agaria' written in 1940 provides wonderful insights into a once vibrant culture comprising of distinctive social customs, striking mythology and totemic practices which were shared by other communities of Central India such as Gonds and Baigas who are generally described as pre-Aryan tribes by anthropologists. In this year of the celebration of the twin centenaries of the industrial scions of the House of Tatas, it is significant to mention that Verrier Elwin dedicated his book on the Agaria to Mr and Mrs J. R. D. Tata.

It may be relevant here to cite some of Verrier Elwin's observations made in his book 'The Agaria' which capture this decisive historical moment of transition from the small scale indigenous iron smelting activities in India to the vast industrial enterprises of iron and steel which were first introduced in India through the endeavours of J.N. Tata, Sir

Dorabji Tata and the House of Tatas with their setting up of what Verrier Elwin describes as the greatest blast furnace in the world in its time.

‘In the present century the iron industry of India has been transformed by the vast enterprises of the House of Tata. Had it not been for certain difficulties of coal and water this book would never have been written, for Jamshedpur would have been established in the Central Provinces and the primitive industry would certainly have been absorbed. For in 1903 it was to Chanda district that Sir Dorabji Tata first went with Mr. Weld on a romantic and thrilling voyage of discovery. Later, the chance discovery of an old map in the Nagpur Museum led Sir Dorabji to Drug and the wonderful reserves of ore at Dalli and Rajhara, even more remarkable than the entire hill or specular iron at Lohara in Chanda. But the supply of coal and water were not equal to the ore, and in the end it was in Bihar that the greatest blast-furnace in the world came to be erected…The ancient smelting industry has of course greatly declined. Yet neither famine, nor foreign competition, heavy taxation, nor a poor technique, social degradation nor the most pitiful earnings have succeeded in altogether destroying the little clay furnaces which may still be found in many parts of India in Bengal and Bihar; in the Santal Parganas, Monghyr, Sambalpur and Orissa; in the Kumaon Hills, in Mysore, in the districts of Malabar, in Salem and Trichnopoly; in Hyderabad; in several States in Central India and Rajputana and above all in the Central Provinces.’’

Of course, what Elwin had to acknowledge as ‘a poor technique’ in industrial terms has been one that is, in its own way, a skilled and controlled process. Agaria furnaces were made to precise dimensions determined by longstanding experience to smelt iron of a high grade. Figure 59 is a sketch of a re-construction of an Agaria iron smelting furnace which was powered by foot operated bellows. Traditionally, the iron smelting process was one that involved the entire community forming the epicentre of their lives. Of the Agaria’s total commitment to their iron smelting craft, Verrier Elwin insightfully wrote, “the Agaria are a people absorbed in their craft and their material; they seem to have little life apart from the roar of the bellows and the clang of hammer upon iron.”

This involvement of the Agarias is captured in one of their folk songs called ‘Chokh Agaria’ from Lapha, translated by Joshi and cited by Bhanu Prakash. This lovely and vivid folk song, which is quoted here, is also remarkable since it indicates that the community, including women, participated in the process of iron working with a real feeling of community that is lost in the impersonal modern day industry. And what better note to end on than to pay tribute to the resilience of these traditional smelters and artisans who have nurtured their traditional systems of knowledge with tenacity against all odds, with one of their own songs!

“ She presses down the bellows
with the strength of her heels.
He wields the heavy hammer with all his might
From the ground he gets stones.
The fire burns fiercely as the bellows blow. .
The little hammer clatters, tinning tanang,

A shower of sparks flies into her breast
He puts it in black
He pulls it out red
Standing he beats it
The chokh girl blows the bellows at the forge
Like a drum it sounds 'Datur Thunda'
How happy I feel
The chokh boy beats with the hammer
The hammer whistles as he swings it round
And I feel very happy “.

Chapter 10:

Ancient Steel Meets Modern Science: Twenty First Century Advances

Historical studies of ancient metallurgy are
an important contribution to understanding
the evolution of man and civilization.
Knowledge gained from understanding
the practices of ancient blacksmiths may well
contribute to the development
of unusual materials of the future.
An old Russian proverb is pertinent
as a closing remark on this subject:
The best of the new is often the long forgotten past"

Oleg Sherby and Jeff Wadsworth
in Progress in Materials Science, 1980

The Future

The future, it has been said, is difficult to predict. But the one thing about the future that we can predict with confidence is that it will definitely shed new knowledge on the past! As human knowledge and scientific approach expand, the spirit of enquiry is aided by truly extraordinary developments. The Rosetta Stone is famous for the help it gave in deciphering the hieroglyphic carvings by the Egyptians, as this stone had both the hieroglyphics and its Greek version. The known Greek language helped to read the past. As C S Smith has remarked, this has some limitations, as the written records of the ancients may not always be reliable. The developments in experimental sciences have given birth to the subject of archaeometallurgy. Thus it is possible to look at the wrought products of ancient civilizations, establish their dates, their chemistry and their provenance and reconstruct ancient technologies. Earlier chapters described how the optical microscope and mechanical testing have shed new light on wootz steel and the Damascus blade. As scientific advances continue, even more powerful instruments become available. Perhaps of equal importance is the development in theory. In the twenty first century, one can expect more illumination on these subjects. This chapter covers two advances in recent times to give a flavour of what might be expected. One is nanotechnology and the other is quantum mechanics.

Materials Science Tetrahedron and Wootz Steel

As indicated earlier, the investigations on wootz steel in 19th century Europe led to the foundations of what we understand today as the central paradigm of materials science. This is based on the idea that the processing of a material leads to a structure, which has a definite combination of properties. This set of properties in turn defines the performance of the possible products that can be made out of these materials. Merton C Flemings captured these four defining ideas as the four corners of a tetrahedron (Figure 60). It will be noted that no particular material is mentioned. It applies equally well to metals, ceramics, polymers and composites. It is this powerful generalization that has made materials science a powerful, pervasive and enduring concept. It applies to steel and sand, nylon and nickel, bone and bronze. The past decade has added one more idea to this quartet of the conceptual framework, namely modelling. As processing, structure and properties become complex, it is possible for us to resort to modelling and simulation. Figure 61 represents the materials science hypertetrahedron for wootz steel. Individual vertices represent processing, structure, properties, performance and modelling. The facets of Buchanan furnace, the iron-carbon diagram, the microstructure of dendrites in the as-cast state and spheroidised cementite in the forged material, the superplastic elongation, and the Damascene marks are displayed with emphasis on the strong interconnections among them.

Nanotechnology and the Damascus Sword

Today the world is agog with the promise of nanotechnology. While the height of human beings is of the order of a metre, a nanometer is one billionth of a metre. Thus we are referring to materials, which are close to molecules in the length scale. The potential of makings things on a small scale was first visualized by Richard Feynman in a famous after dinner speech as far back as 1959, entitled "There's Plenty of Room at the Bottom"

I can hardly doubt that when we have some control of the arrangement of things ON A SMALL SCALE we will get an enormously greater range of possible properties that substances can have."

In the same lecture Feynman threw a major challenge:

"It would be very easy to make an analysis of any complicated chemical substance; all one would have to do would be to look at it and see where the atoms are. The only trouble is that the electron microscope is one hundred times too poor…I put this out as a challenge: Is there no way to make the ELECTRON MICROSCOPE more powerful?"

It is remarkable that after four decades, an aberration free electron microscope has been built and is offering an unprecedented view of the architecture of nanonmaterials.

Since the eighties, enormous interest has marked this field. But it is interesting to recall that long before the scientific realization came, nanomaterials were in use. Three examples will illustrate this. The stunning blue colour seen in Mayan pottery, murals and ceremonial artefacts has always attracted admiration. M. Jose-Yacaman and his colleagues used sophisticated electron microscopy to show that this paint contained an amorphous silicate substrate with inclusions of metal nanoparticles as well as oxide nanoparticles on the surface. It is this nanosize that led to the brilliant colour effects. In the cathedrals built during the Renaissance in Europe the stained glass windows owe their resplendent colours to nanometric metals. Early in the twelfth century, Theophilus, a German monk, wrote a description of the techniques of making stained glass. The basic methods have hardly changed. Glass was made by melting sand, potash and lime together in clay pots and coloured by the addition of metallic oxides - copper for red, iron for green, cobalt for blue and so on. In Paris the glowing reds and purples of Notre Dame Cathedral's famous stained glass windows owe their colour to one precious metal: gold. The artisans across Europe had recipes for their glass, throwing soluble gold salts into the mix, knowing that only gold particles of very small sizes gave them their vibrant colours. A similar occurrence is the tiny metal particles that gave lustre to the 15th century Italian ceramics. Potters in the Umbrian town of Deruta made ceramics with iridescent or metallic glazes. Some had the appearance of gold, while others had iridescence, changing colours when viewed from different perspectives. The Italian researchers have now determined that the red and gold – lustre glazes came from nanoparticles of copper and silver. It is evidently a case of nanotechnology meeting alchemy! In 1857 Michael Faraday produced colloidal gold and saw that the colour of gold varied from blue to yellow-green with changing particle size. This is a kind of alchemy where the optical property of a metal was changed by varying its size. When the size gets to nanometric level, quantum mechanical effects become dominant.

The best-known application of nanotechnology is in electronics. Gordon Moore, Founder of Intel, made the famous observation in 1965 that there will be an exponential growth in the number of transistors per integrated circuit and that this trend will continue. Due to relentless technological advances this doubling of transistors every two years has been maintained. It must be realized that the dimensions shrink correspondingly. In 2004 Intel produced the 65 nanometre transistor, a magnificent accomplishment indeed and a great tribute to their perseverance. This invention has in turn fuelled the revolution in computers, communication and information technologies. The ubiquitous mobile phone, digital camera, the DVD player and the laptop computer have come to define the digital life of modern civilization.

An interesting question about nanotechnology and wootz steel arises. In 2004, Werner Kochmann and his German colleagues have reported on the observation of nanowires in ancient Damascus steel. B Zchokkke had examined in 1924 a sabre belonging to the Swiss collector, Henri Moser. It is authenticated as a product of the legendary blacksmith Assad Ullah of the seventeenth century. The elemental analysis showed 2.4 wt% carbon. A specimen prepared for transmission electron microscopy was analysed by energy dispersive analysis of x-rays. It showed the presence of iron, carbon, boron, neodymium, cerium, samarium and thorium. Kochmann had earlier observed weak radioactivity in a sword from Manfred Sachse. Indian metallurgists were perhaps adding rare earth and thorium phosphates as a source of phosphorus.

Contemporary sophisticated characterisation techniques were used by the German investigators. These included Focussed ion beam thinning, Field-emission scanning electron microscopy and Field emission gun transmission electron microscopy. A high density of nanowires was identified at different points of the samples (Figure 62). A high resolution image of the nanowire revealed lattice planes of cementite. A Fourier transform of the image confirmed the orthorhombic structure of the cementite. A high density of dislocations was observed between the nanowires. For studying the mechanical properties a nanoindenter was used to measure the indentation –displacement curves (Figure 63). The nanohardness of cementite and pearlite could be measued separately. Most previous measurements were on a coarser scale and could not distinguish the behaviour of individual microconstituents. This indicated striking difference in the inelastic behaviour of these twom phases. This study enabled them to describe the Damascus steel in modern idiom. This steel represents a combination of a high yield stress for the onset of plastic flow and a large ultimate strain. Both together lead to high fracture toughness. The conventional experience in metallic materials is that as strength goes up, ductility and concomitant toughness is reduced. Then how did the ancient Indian metallurgist produce steel with the unusual combination of properties? It is now becoming clear that the ultra high carbon imparted the necessary strength. In the usual microstructure, cementite will occur at grain boundaries and lead to embrittlement. But the superplastic forging used to make the swords broke up the cementite, leading to its spheroidal morphology. In addition the size of ferrite and cementite got refined. This leads to enhanced ductility and toughness. What is exciting is the possibility that in some cases the refinement of cementite proceeded to the nanometric scale. The German authors speculate that the nanowires may have influenced the growth kinetics of the microstructure. In addition they acted as obstacles for dislocation as well as crack propagation.

Greg Olson of Northwestern University, USA, has observed another instance to support the argument that the ancient sword makers were accidental nanotechnologists. TEM analysis has shown nanometre scale patterns of carbon in the hard edge of the steel. This may have been due to spinodal decomposition. This is a particularly exotic transformation, where small changes occur over large volumes, in contrast with normal nucleation and growth, where large changes occur over small volumes. In this process a high carbon martensite becomes unstable and decomposes into constituents with different compositions. Olson terms this as ‘self-assembled heterophase nanostructures’!

Quantum Blacksmiths

Materials science came into being due to the investigations into the properties of wootz steel. As it continued to evolve in the latter half of twentieth century, it took an amazing turn. The question was raised as to whether new materials are to be discovered by experiments or whether it will be possible to design them from first principles. Quantum mechanics offers powerful insights into the structure and behaviour of atoms. Will it not be possible simply to compute and design alloys inside the computer? A major contributor to this field is Greg Olson. He has argued that as the new millennium unfolds, it is ushering in an Age of Design marked by new materials that go beyond the dreams of the medieval alchemists.

Greg Olson was with C S Smith in the Massachusettes Institute of Technology and was deeply influenced by Smith’s view of materials. Smith had described a universal multilevel nature of structure with strong interactions among the various levels. Indeed, Smith took his own inspiration from the work of Rene Antoine Ferchault de Reaumur’s sketch of the quench-hardened steel. Reaumur had proposed that a single grain of steel on enlargement would show a set of molecules and voids. Further magnification will show a substructure of molecules and still higher magnification will show a periodic arrangement of spheres. In modern terminology this leads to multi-scale architecture of materials.

Figure 64 illustrates the powerful modelling and observational techniques used by Olson. At the coarsest level, solidification is the chemical banding visible in the Damascus swords. It is possible to employ thermodynamics to predict the structures at the 10 μm scale. This may be called “solidification design”. At the next lower level of 1μm, the structural changes that take place on heat treatment can be modelled. These follow various phase transformations. This may be termed as “ transformation design”. When size is further reduced to 0.1 μm scale, design enters the micro-mechanics regime. Grain refining can lead to such small grain sizes. It is possible to use continuum mechanics to follow the flow and fracture of materials. The most exciting level is the next level – the nanoscopic level. The realm of quantum design begins at the electronic level- the finest level relevant to real materials. A profound advance came with the development of computational quantum mechanics and its extension via density functional theory. This step led to the 1998 award of the Nobel Prize in chemistry to John Pople and Walter Kohn.

The need for modelling and design is best appreciated, when it is realized that the possible combinations of elements for making alloys and compounds is truly enormous. It typically takes a hundred million dollars over two decades to fully develop and qualify a new material using the experimental approach.

Olson went on to found a company christened as QuesTek Innovations. Successful examples from the Northwestern University efforts include a stainless steel bearing for space shuttle applications, high strength, high-toughness steels for aircraft landing gear and armour applications, and a new class of ultra-hard steels for advanced gear and bearing applications. Of immense interest to wootz steel is the Dragon-slayer Project. Olson in a dramatic fashion enlisted freshman and upper class design teams to use the most modern and sophisticated computational methods to recreate an ancient steel. As ancient Western literature is replete with dragons, it was felt that a sword named Dragon-slayer would have maximum market appeal. The mystique of the Samurai sword provided the inspiration, as even five centuries ago these swords outperformed all other swords. So the performance specification had to be comparable. In addition, high temperature resistance was an added requirement, as the sword had to deal with fire-breathing dragons! In terms of form for the weapon, a historical precedent of a patterned double-edged sword was to be the example. As a supernatural element is necessary in fighting such mythical beasts, the iron had to be of extra-terrestrial origin. In this meteoritic iron, which as we have noted in an earlier chapter came from the sky, was the natural primary ingredient. This fusion of ancient legend and modern science proved successful. But it is important to note that in spite of the fanciful tale the underlying science was of the most advanced kind using powerful computation and sophisticated experimental techniques.

Amorphous Steel: New Horizons:

Metallic materials in use for several millennia were all crystalline with a periodic arrangement of atoms. But glass, which has been in use for a similar period, was noncrystalline with a random arrangement of atoms. In a serendipitous discovery in 1960 Pol Duwez, California Institute of Technology, USA quenched a gold-silicon alloy from the liquid state at a spectacular cooling rate of a million Kelvin per second and found that it had solidified as a metallic glass. This was indeed a new class of materials. Soon scientists discovered iron-boron metallic glasses. However, all these glasses were only a few microns thick because of the high cooling rate required. This changed dramatically in 1988, when Akihisa Inoue, a successor at Tohoku University to Korato Honda, found a way of lowering the cooling rate so that centimeter thick bulk artefacts can be produced. Inoue realised the importance of having an alloy made of as many components as possible. In a fashion reminiscent of Faraday, Breant and Anossoff he experimented with a large number of systems and found very many bulk metallic glasses. This indeed heralded a revolution. There was keen interest to develop iron based bulk metallic glasses. In 2004 Joe Poon, Gary Shiflet and Vidyabharathi Ponnambalam, University of Virginia, USA have reported the preparation of Fe-Mn-Cr-Mo- (Y, Ln) -C-B glass with a thickness of 7mm. This is a true witch's brew containing as many as eight elements. This glass was three times stronger than conventional steel and had superior corrosion resistance. It can be formed easily in the supercooled liquid state, very similar to superplastic crystalline materials. Among the many applications lighter but harder armour peiercing projectiles are envisaged- a modern day Damascus blade! One can expect with eager anticipation further developments. Controlled crystallisation can lead to nanocomposites with an enhancement of many desirable properties and perhaps with a damascene structure!

Back to the Future: The Return of the Copper Age

In many ways the current age belongs to silicon, which forms the heart of the chip that drives modern computers. As researchers worked in a relentless fashion to reduce the size to nanometric dimensions, a peculiar problem arose. Aluminium was used to connect the various components. But as the size was reduced it did not have adequate conductivity to dissipate the heat that was generated. Copper was an alternative but it tended to poison silicon. In a remarkable development, IBM found a way to isolate copper from silicon. Copper conducts electricity with 40% less resistance. This in itself leads to lower heat generation. A key technology for patterning thin films of copper was called Damascene in relation to the Damascus sword patterns. Figure 65 illustrates this. Over 58 million transistors can be placed in a chip that is only 66 milimetres square! This is called by the company as being mightier than the sword. It is fascinating to note that the metal copper, with which mankind began its journey, comes back with fresh force in a completely different setting.

Summing Up

The basic paradigm of materials science states that a specific processing route will lead to a definite microstructure with associated properties and a resultant performance. It is therefore astonishing that in the case of Damascus swords we have two different kinds - the genuine and the pattern-welded. Entirely different paths are followed, with the microstructure being similar but not identical. Yet both the monolithic Damascus sword and the laminated composite of pattern-welded sword, possess very similar combination of strength, ductility and toughness. There is perhaps no other parallel of this type of duality in materials science. That the ancient Indian blacksmiths found the route for wootz or true Damascus steel by empiricism needs to be lauded. That the advanced material of wootz or true Damascus steel that they fashioned, ruled across continents over millennia, continues to astonish us. In this twin centenary year celebrating the modern architects of Indian steel, there can be no better resolve for the young Indian metallurgist than to develop new steels and new materials that will stand the test of time.