Indian Journal of Traditional Knowledge
Vol 24(9), September 2025, pp 809-820
DOI: 10.56042/ijtk.v24i9.17079

Historical footprints of iron metallurgy works in ancient India: A comprehensive review

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Received 11 February 2025; revised 11 August 2025; accepted 08 September 2025

The practice of iron metallurgy in ancient India represents a profound and influential aspect of the subcontinent's history, with far-reaching implications for culture, technology, and society. The origins of iron production in India can be traced back to the early 2nd millennium BCE, coinciding with the transition from the Bronze Age to Iron Age. This technological revolution marked a pivotal moment in human history as the knowledge and mastery of ironworking gradually spread across the Indian subcontinent. The present review article delves into the evolution of iron metallurgy in ancient India including early iron working and its time frame, and the discussion of iron through the lens of ancient Indian literature. It showcases iconic examples of ancient iron craftsmanship, such as the Delhi Iron Pillar, iron beams at Sun Temple Konark, Dhar Iron Pillar, Damascus steel, and India’s iron and steel industry. Furthermore, the scientific and analytical analysis of iron samples are also included in the present study. In essence, the footprints of iron metallurgy in ancient India guide us through the annals of history, revealing a story of technological innovation, cultural significance, and enduring relevance that continues to inspire and inform our journey into the future.

Keywords: Ancient India, Footprint, Iron, Metallurgy

IPC Code: Int Cl.[25]: C22C 9/00, C22C 38/00

India’s rich history is adorned with remarkable achievements in various fields, and one of its most notable contributions lies in the realm of metallurgy. Among the metals that played a pivotal role in shaping the ancient Indian civilization, iron stands out as a significant milestone in the technological advancement of the subcontinent. The origins of iron metallurgy in India can be traced back to antiquity, revealing a fascinating journey of innovation, trade and cultural exchange. The discovery and mastery of iron metallurgy revolutionized various aspects of society, from agricultural practices to warfare and trade. Many historical sites across the Indian subcontinent have been endowed with ancient temples, monuments, and others such as sculptures, pillars, coins, and so on, providing a powerful testament to the craftsmanship of ancient Indian artisans. This demonstrates that Indian civilization, in addition to being rich in philosophical and ethical traditions, was quite advanced in material prosperity.

The material advancement of humans during the ancient period progressed through three broad eras that can be chronologically visualized as Stone Age, Copper Age, and Iron Age. As early as the Neolithic period (c. 7000 BCE - 1000 BCE), people had started using tools such as knife, chisel, axe, hammer so on, made of bones and stones[1-4]. The Chalcolithic period, also known as the Copper-Stone Age (c. 2000 BCE - 700 BCE), followed the stone age and was associated with the Saraswati-Sindhu civilization. During the Chalcolithic era, tools were made of both copper and stone (Chalco = "copper," Lithic = "stone"). Copper and its alloy *i.e.*, bronze were utilized to make beads, tools, rings, bangles, and so on[5,6]. Further, the excavations at different locations such as Harappa in Punjab and Mohenjo-Daro in Sindh (both now in Pakistan) demonstrate that the developed era of this civilization (also known as the Bronze-age Harappan Civilization) spanned much of the Indian subcontinent

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between c. 2500 BCE and 1800 BCE[7,8]. This civilization is characterized by the discovery of terracotta and bronze objects, including figurines, ornaments, seals, stone beads, and uniquely crafted black-and-red pottery. Furthermore, the emergence of iron technology provided a significant impetus to human development, ushering in the Iron Age (c. 1200–600 BCE) in India[9-11]. Iron was in use in southern India even before 1000 BCE, while its adoption in the upper Gangetic plains and eastern regions of India began around 1000 BCE[12].

Iron replaced copper and bronze as the metal of choice for making tools and weapons. This change was due to large availability of iron ore and the ease with which it could be smelted and forged. The technique of making steel and iron in India has been referenced in Vedic scriptures (c. 1500 BCE - 500 BCE)[13]. Over time, the process of iron production evolved significantly, with artisans developing a high level of skill and expertise in ironworking techniques. Evidence of iron production has been found across various regions of India, highlighting the country's rich and ancient tradition of ironworking[14]. A remarkable instance is the iron pillar located in Delhi, dating back to around 400 CE, which is renowned for its exceptional resistance to corrosion despite standing for over sixteen centuries[15]. This has piqued the interest of researchers from India and across the globe. Iron technology has long held a prominent place in the Indian subcontinent, and numerous studies have been performed on the iron pillar in order to unlock the technology behind these unique features[16-22]. Further, the iron beams used in the Sun Temple at Konark, constructed around 1250 CE in Odisha, serve as another testament to the advanced ironworking skills present in ancient India.

The present work aims to shed light on the footprints of iron metallurgy works in ancient India. As we confront contemporary challenges, from environmental sustainability to technological advancement, this exploration of the past serves as a guiding light, offering solutions and innovative approaches for a better and more sustainable future. In essence, our motivation lies in unraveling the richness of ancient Indian iron metallurgy to learn from the past and to pave the way for a brighter future.

Evolution of iron metallurgy in ancient India

There was a long evolutionary trend in the history of iron metallurgy, as evidenced by archaeological data. The evidence suggests that it took many centuries of continuous effort to enhance and perfect metallurgical practices. Iron technology progressed not only from slag-rich wrought iron to rustless steely iron but also from the creation of small tools to the construction of large-scale structures. In this regard, it is worth to mention Chakrabarti'[23,24] assertions that "there is no logical basis to connect the beginning of iron in India with any diffusion from the west, from Iran and beyond" and "that India was a separate and possibly independent centre of manufacture of early iron." It is noteworthy that the large-scale iron smelting was undoubtedly existed in India for a very long time. Significantly, the Asura and Agaria were the two major tribes involved with the smelting of Iron in India[25]. The Asura tribe, residing in the Chotanagpur plateau, is traditionally recognized for its indigenous iron-smelting practices[26]. While Agaria, another tribe practicing iron smelting on large scale, lived in Madhya Pradesh, Andhra Pradesh, Eastern Uttar Pradesh, Bengal, Bihar and Orissa. The iron metallurgy developed in India in three stages having different time periods:

- "Early Iron Age" (by the end of the second millennium BCE – 700 BCE)
- "Middle Iron Age" (800-100 BCE)
- "Late Iron Age" (100 BCE-600 CE)

The 'early Iron Age' cultures arising in five different zones of India which are: (i) Painted Grey Ware (PGW) culture in north India (ii) Cairn Burial culture in north western India (iii) Black and Red Ware (BRW) culture in Gangetic plains and Deccan plateau (iv) Megalithic culture of Peninsular India and (v) Megalithic culture of central India.

Bimetallic artifacts such as bronze and gold alloys were generally ornamental in the early Iron Age[27]. Even for hunting weapons and military equipment, bronze was not entirely replaced by iron. Reflecting a gradual development of the medium based on bone prototypes, iron implements in this era occasionally resembled early Neolithic-Chalcolithic bone or stone objects. From this time on, there have been certain instances of deliberate carburization.

During the 'second stage' or the 'middle Iron Age', iron smelting became prevalent across India, with techniques like carburization and quenching being recognized and practiced. In regional languages like Pali and Sanskrit texts of fifth to fourth century BCE, a wide range of iron artifacts are mentioned in Indian literature. According to excavation reports and the literature studies, the iron smiths were capable of producing high-quality iron and steel at that time. It is crystal clear from numerous examples cited above that the steel ingots and swords were presented as gifts, and surgical instruments composed of steel were also manufactured[27]. The production of carburized iron in India stimulated both inter-regional and long-distance trade networks. Industries such as bead-making and ceramics were developed to meet the demand of both local and overseas traders.

The 'third stage', referred to as the 'late Iron Age', is recognized for reflecting a more advanced phase of iron metallurgy. Iron metallurgy had substantially evolved by this time in Indian history, as had the practical applications of iron artifacts. Iron was used to make a wide range of tools, weapons, implements, home goods, and everyday items. A well-known example demonstrates the mastery of Iron metallurgy is the Delhi Iron Pillar which was made in an age of culmination of technological skills, and is also known worldwide for its corrosion resistance property. During this period, high-quality steel was reportedly used to manufacture surgical tools and advanced weapons like swords, tridents, and caltrops. The superior quality of iron and steel produced in India attracted trade from other parts of the world, making these materials highly sought-after both domestically and internationally. As a result, India experienced a flourishing era marked by significant progress in multiple domains. Thus, the period which started in the late Iron Age, was known as the "Golden Age" of Indian history during the Gupta Empire[13,28].

Early iron working

There is relatively little evidence of archaeometallurgy at sites in north and central India such as Malhar (c. 1800 cal. BCE), Raja Nal-ka-tila (c. 1400 cal. BCE), Atranjikhera (1265-1000 cal. BCE) in Uttar Pradesh and Noh (885-580 cal. BCE) in Rajasthan[12,29,30]. A study examining urban development in the Allahabad district between c. 1000 BCE and 300 CE found evidence of slag at certain sites, though only a few iron artifacts were uncovered[31]. However, determining details regarding local manufacturing from accessible reports is extremely challenging. Early Iron Age sites in central and north India have been excavated, including Baba Wali Pahari, Raja Nal-ka-tila, Malhar, and Dadupur[29]. Significantly, evidences such as slag heaps, tuyeres, and finished iron artifacts found at those excavations, are associated to smelting. Tewari (2003) proposed three time periods during which iron working was done at these sites: c. 1200-900 cal. BCE, c. 1400-1200 cal. BCE and c. 1800-1500 cal. BCE. Allchin and Allchin[32] and Gaur[30,33] proposed that iron production in the mid-Ganga Valley dates back to c. 1200-1000 cal. BCE. Similarly, Chakrabarti[9] suggested a timeframe of c. 1270 cal. BCE for ironworking activities in the same region. Painted gray ware (PGW) pottery has also been discovered in the Central Himalayan regions of Purola and Thapli[34]. Evidence of slag and crucibles have also been recorded in the Kumaon and Almora districts within the Central Himalayan region. Notably, slag discovered at the Uleni site in Dwarahat, located in the Almora District, has been dated to the early first millennium BCE (c. 1022-826 BCE)[35,36]. The researchers suggested that the Ganga Valley's inhabitants either sourced locally available iron ore or acquired processed iron artifacts from the Central Himalayan region. Agrawal and Kharakwal[37] concluded that the Central Himalayan region had a significant role in the dissemination of iron metallurgy across the Ganga Valley.

The Early Iron Age in India is characterized by three key types of diagnostic pottery: PGW (c. 800 - 350 BCE); Northern Black Polished Ware (NBPW) (c. 600-100 BCE); and BRW (c. 900 BCE-100 CE)[33,38-41]. Although there is disagreement among the researchers over dating of BRW, Chakrabarti[12] suggests that it precedes PGW whereas Habib[42] argues that it postdates PGW in peninsular India. In the Ganga River valley, the Early Iron Age is also linked to PGW culture[27]. Iron artifacts are connected with PGW and NBPW at upper Gangetic Valley sites like Atranjikhera, Hastinapur, and Noh[12,33,38,40] whereas NBPW and BRW are linked with iron artifacts at Chirand and Mahisdal in eastern India[32] and Nagda, Eran, and Navdatoli[9]. Interestingly, many iron implements and tools have been recovered during the PGW phase at Atranjikhera, demonstrating advanced iron technology[33].

Time frame

The origin and time frame of iron artifacts and ironworking in India remain highly debated topic among researchers. According to the Ancient Indian text, the *Rigveda*[43], the second millennium BCE is frequently proposed as the time frame. According to early academics, iron-working began in India around 700-600 BCE[44]. Following research efforts and dating technology have pushed this date back towards second millennium BCE[12] along PGW. Regarding the origins of technology, Chakrabarti[23,24] proposed that

India was a distinct and potentially independent hub of early iron production. Radiocarbon dating of iron-bearing deposits from sites such as Nagda and Eran in central India, Kaushambi, Atranjikhera, and Jakheranear Uttar Pradesh, and Hallur in Karnataka, indicate iron use around 1000 BCE[23,10]. The technical investigations of iron materials from Komaranahalli (Karnataka) dated about 1000 BCE revealed that the local smiths were capable of working with large artifacts which suggests a long history of experimentation and accumulated expertise over centuries[45]. Sahi[46] noted the occurrence of iron within the Chalcolithic deposits at Ahar and proposed that "the date of the beginning of iron smelting in India may well be placed as early as the sixteenth century BCE" and that "by about the early decade of the thirteenth century BCE, iron smelting was definitely known in India on a bigger scale." The Indian subcontinent's Early Iron Age may have succeeded the Indus Valley tradition and Late Harappan culture. As already stated, the early Iron Age in India is linked with three significant diagnostic pottery types: PGW, NBPW and BRW. In northern India, the Iron Age cultures were associated with PGW culture (1200-600 BCE) and NBPW culture (700-200 BCE), whereas in South India, it was associated with BRW and Russet Coated Painted Ware (RCPW). In Central India, sites like Nagda, Navdatoli, and Eran were linked to BRW and NBPW[9], while in Eastern India, Chirand and Mahishadal show similar associations with both BRW and NBPW[32]. Tewari[29] identified three distinct phases of iron-working activity at these northern Indian sites: c. 1200-900 cal. BCE, c. 1400-1200 cal. BCE and c. 1800-1500 cal. BCE.

More recently, Ranjan and Sivanantham[47] claimed that the Iron was initially introduced in Tamil Nadu during the first quarter of the fourth millennium BCE. Archaeologists discovered iron objects at six sites in Tamil Nadu, dated back to 2953-3345 BCE (*i.e.,* 5000 to 5400 years old). A Sarcophagus burial was found at Kilnamandi (Tamil Nadu), dated to 1692 BCE, and is the earliest-dated burial. Moreover, the identification of iron-smelting furnaces at sites such as Mayiladumparai, Kilnamandi, and Perungalur etc. demonstrates the technological sophistication in producing the durable iron tools and weapons in that region.

Ancient Indian literature related to iron

Various types of iron have been mentioned in well-known ancient Indian text, *Rasaratnasamucchaya*[48] as mentioned in Shloka (Fig. 1). This shloka states that there are three types of iron known as Munda loha (cast iron), Tikshna loha (wrought iron) and Kaanta loha (carbon steel). These are further classified as:

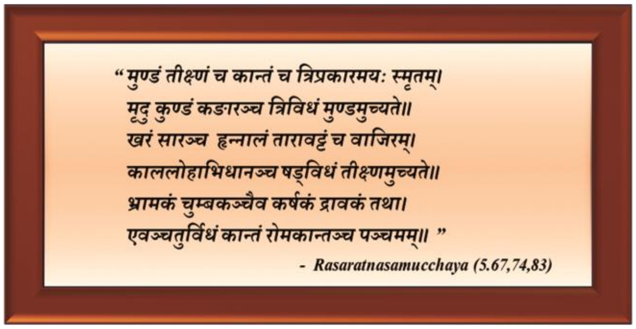
1. Munda loha: Mrudu, Kunda, Kadara
2. Tikshna loha: Khara, Saara, Hrunnaala, Taaravatta, Vaajira, Kaalaloha
3. Kaanta loha: Bhraamaka, Chumbaka, Karshaka, Draavaka, Romakaana

Moreover, the method of purifying different types of iron has also been described in *Rasaratnasamucchaya*[48] as mentioned in Shloka (Fig. 2).

In this sloka, four methods of iron purifications are mentioned which are as follows:

First method: Take small pieces or sheets of iron (of any type of iron), coat them with rabbit’s blood, and heat them in a fire. By doing this three times, all the defects of the iron are removed, and the iron becomes purified.

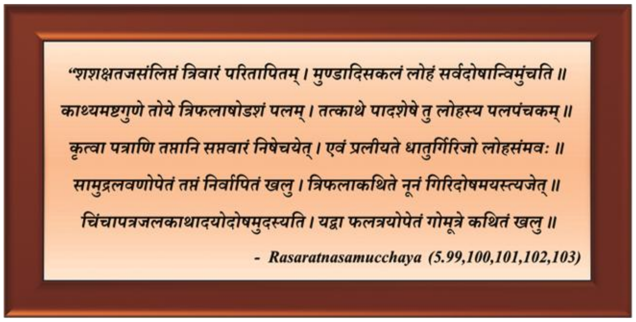
Second method: Take 20 tolas (a unit of weight) of iron sheets, heat them, and quench them in a decoction prepared by boiling eight times the amount of water with 60 tolas of Triphala (mixture of three dried fruits) until only one-fourth of the liquid remains. By quenching the heated iron seven times in this solution, the mineral impurities of the iron are removed.



“ मुण्डं तीक्ष्णं च कान्तं च त्रिप्रकारमयः स्मृतम्।
मृदु कुण्डं कडारञ्च त्रिविधं मुण्डमुच्यते॥
खरं सारञ्च हृन्नालं तारावट्टं च वाजिरम्।
काललोहाभिधानञ्च षड्विधं तीक्ष्णमुच्यते॥
भ्रामकं चुम्बकञ्चैव कर्षकं द्रावकं तथा।
एवञ्चतुर्विधं कान्तं रोमकान्तञ्च पञ्चमम्॥ ”

- *Rasaratnasamucchaya (5.67,74,83)*

Fig. 1 — Different types of iron mentioned in ancient Sanskrit text (Shloka), *Rasaratnasamucchaya*[48]



“शशक्षतजसंलिप्तं त्रिवारं परितापितम् । मुण्डादिसकलं लोहं सर्वदोषान्विमुंचति ॥
काथ्यमष्टगुणे तोये त्रिफलाषोडशं पलम् । तत्काथे पादशेषे तु लोहस्य पलपंचकम् ॥
कृत्वा पत्राणि तप्तानि सप्तवारं निषेचयेत् । एवं प्रलीयते धातुर्गिरिजो लोहसंमवः ॥
सामुद्रलवणोपेतं तप्तं निर्वापितं खलु । त्रिफलाकथिते नूनं गिरिदोषमयस्त्यजेत् ॥
चिंचापत्रजलकाथादयोदोषमुदस्यति । यद्वा फलत्रयोपेतं गोमूत्रे कथितं खलु ॥

- *Rasaratnasamucchaya (5.99,100,101,102,103)*

Fig. 2 — Methods of iron purification mentioned in ancient Sanskrit text (Shloka), *Rasaratnasamucchaya*[48]

Third method: Prepare the Triphala decoction as above, add sea salt to it, heat the iron sheets, and quench them seven times; after this, the iron is purified.

Fourth method: Extract juice from tamarind leaves, or prepare a decoction from tamarind leaves, or use a Triphala decoction prepared with cow urine. Heat the iron-sheets and quench them seven times in this solution, and all types of iron will become purified.

The iron and steel producing technology in India is referred in the scriptures of Vedic period (c. 1500 BCE - 500 BCE)[13]. After silver and gold, AYAS (iron) was the third Rig-Vedic metal. Moreover, the use of fire for extracting iron and other metals such as gold, silver, tin, lead, and copper-from the havanakunda is mentioned in a verse of the *Yajurveda*[49] (SI-2). Further, *Susruta Samhita*[50] mentions the method of production (c.700 BCE) of more than a hundred surgical tools composed of Fe-C alloys, as well as the process of heat treatment to create sharp edges. Also, the technique of iron extraction and iron-carbon alloying is referenced in *Rasaratnasamucchaya* (c. 1200 CE-800 CE)[13,51]. In *Khargalaksnam* (Chap. XVIX, sloka 23-26), Varahamihira (c. 550 CE) mentions the method of carburization and hardening of iron swords[52]. It is worth noting that the iron producing technology existed to meet man's need for battle and peace, as evidenced by weapons and implements mentioned in *Rig-Veda* and the *Puranas*.

Applications and well known examples of ancient iron metallurgy

One of the most significant metals having the greatest influence on humanity is iron. On earth, iron is typically found as iron ore rather than as a useable metal in solid form. The most prevalent iron ores from where iron is extracted are magnetite, hematite, limonite and goethite. Since the furnace temperatures in ancient times were not high enough to melt iron (which has a melting point of 1536°C), iron was extracted by heating iron ore with charcoal. This process produced a soft, spongy mass that was subsequently hammered to form the desired shapes. The classification of iron produced in ancient India includes: (i) wrought iron with little or no carbon, (ii) steel with upto 1.7% carbon (iii) cast iron with upto 7% carbon[10]. Remarkably, India is known for producing Wootz steel, which is renowned for its outstanding quality. The majority of ancient iron artefacts are composed of wrought iron. World-famous ancient artefacts such as the Delhi Iron Pillar, the iron beams at Konark Sun Temple, the iron pillar in Dhar etc. demonstrate the extraordinary achievement of iron-making technology in ancient India, which are covered in detail as follows:

Delhi iron pillar

One of the miracles of iron metallurgy is the iron pillar in Delhi (Fig. 3a), stated as "Rust-less Wonder" which has been acknowledged universally as one of the most significant metallurgical achievements in the

Fig. 3 — (a) "Corrosion less" Iron Pillar in Delhi, (b) the decorative bell capital at the top of pillar, reproduced under a Creative Commons Attribution-Share Alike 4.0 International license

history of ancient India. This Iron Pillar is 7.31 m long located in the Qutub complex in Mehrauli, New Delhi, India. Furthermore, the design and craftsmanship of decorative bell capital of this iron pillar demonstrates the high degree of ironworking expertise of the ancient Indian blacksmiths (Fig. 3b).

The pillar was constructed from wrought iron through solid-state reduction of iron ore using charcoal, followed by horizontal forge welding[53-55] as shown in (Fig. 4). The pillar was ingeniously constructed by forging and hammer-welding chunks of hot pasty iron in sequential steps rather than being cast in a single piece. Despite being exposed to the ambient environment for more than 1600 years, the pillar is exceptional for its resistance to corrosion. Numerous studies related to compositional analyses have been performed by the researchers worldwide in order to uncover the mystery behind the corrosion resistance property of Delhi Iron Pillar[15,16-20,53-60]. R. Hadfield[57-59] was the first to analyze the composition of the iron pillar. Later, more comprehensive investigations were performed to gain deeper insights into its compositions with their findings summarized in Table 1. As suggested by Indian metallurgists, the corrosion resistance of iron pillar is ascribed to the unique composition of Fe[20] or to its high slag content[21,61]. One of the English investigators, J. C. Hudson[16] emphasized the climatic conditions and suggested that it is a clean largely dry atmosphere of Delhi in which the pillar had stood for centuries. Moreover, the bottom part of the pillar, buried in moist ground than atmosphere, has a thick layer of rust over 1 cm and deep corrosion pits up to 10 cm[15]. This suggests that the climate, rather than composition, is the primary attributor for the corrosion-resistance of Delhi Iron Pillar. Following elaborate scientific studies by Balasubramaniam *et al.*[17,18,60] it was concluded that the presence of phosphorus in iron helps to form a protective crystalline layer of iron

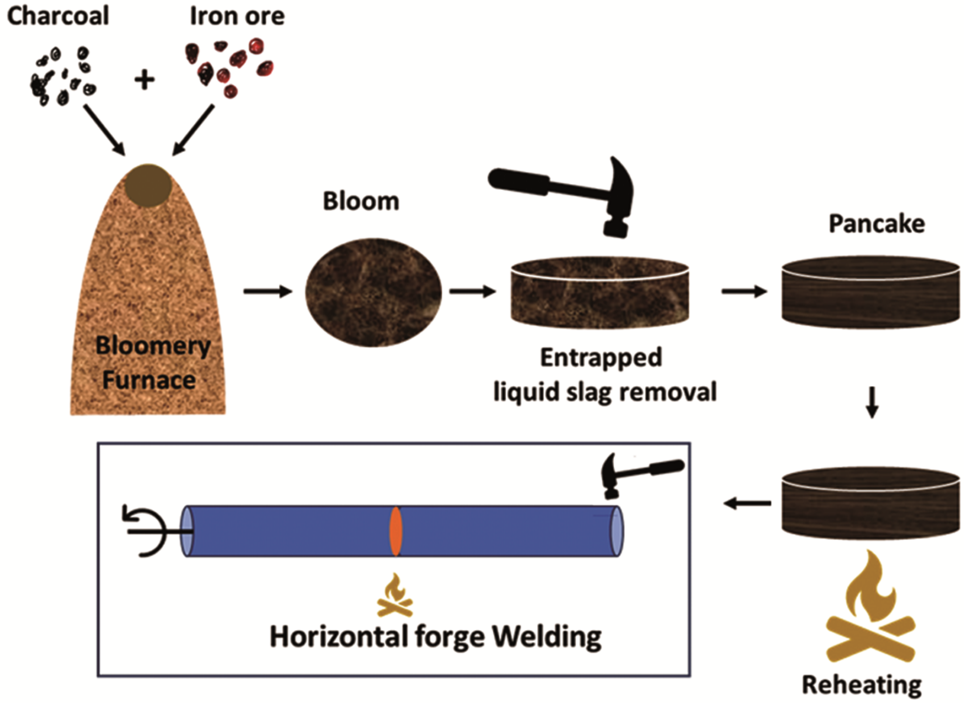


Fig. 4 — Schematic methodology for the production of the Delhi Iron Pillar

Table 1 — Compositions of Delhi Iron Pillar[57-59,21,15,62,20], Konark Sun Temple[63] and Dhar Iron Pillar[64]

Fe (%)	P (%)	C (%)	Si (%)	S (%)	N (%)	Cu (%)	Mn (%)	Ni (%)	Cr (%)	Ref.
99.72	0.114	0.080	0.046	0.006	0.032	0.034	Nil	-	-	57-59
	0.155	0.28	0.056	0.003	-	-	Nil	-	-	21
99.395	0.25	0.15	0.05	0.005	0.02	0.03	0.05	0.05	-	15
99.67	0.174	0.90	0.048	0.007	-	-	Nil	-	-	62
99.4575	0.280	0.23	0.046	traces	0.0065	-	Nil	-	-	20
99.64	0.15	Traces	-	traces	-	-	Nil	-	-	63
99.53	0.072	0.013	0.06	0.003	-	0.057	traces	0.268	-	64

hydrogen phosphate ($FePO_4·H_3PO_4·4H_2O$). This layer is formed at interface between the metal and the atmospheric rust which acts as a shield, making the pillar more resistant to corrosion. From the aforementioned studies, the corrosion resistance of the iron pillar could be attributed to composition, high purity wrought iron, elevated slag content, high phosphorus, low sulphur content (Table 1) and more importantly the unique climate of Delhi.

Iron beam at the Sun Temple of Konark

The Sun Temple of Konark (Odisha) is a Hindu temple devoted to the sun god 'Surya' which was built in the 13th century CE and declared by UNESCO as a world heritage site in 1984. It is famous for its huge iron beams that support the temple's roof. The iron beams at Konark's Sun Temple (Fig. 5) are a testament of engineering and technological skills of Ancient Indian's craftsman. The iron beams are considerably large, measuring between 5.5 and 6.4 meters in length, with a cross-sectional dimension of 20.32 × 25.4 cm^2. The iron employed in the beams of the Konark Sun Temple has been conclusively identified as wrought iron[63]. The large, rectangular iron beams demonstrate the impressive scale at which iron forging was practiced in ancient India. The iron beams are not forged as perfectly as the Delhi pillar having fairly visible weld lines, cinder marks and residues evident on many of the iron beams[63]. Despite their proximity to the seacoast, the iron beams remain in remarkably good condition, exhibiting only surface-level rusting-likely due to their specific material composition. The composition investigations of a sample from one of the iron beams reveal that its composition closely resembles that of the Delhi Iron Pillar, with no manganese and high phosphorus content, along with traces of sulphur and carbon (Table 1).

Dhar Iron Pillar

Another remarkable monument, the Iron Pillar, located in Dhar, the former capital of Malwa, stands as a testament to the exceptional metallurgical expertise of ancient Indian iron smiths[63-65]. Originally measuring 12.8 meters in length and weighing approximately 7 tonnes, the Dhar Iron Pillar is nearly twice as tall as its counterpart in Delhi. At present, it lies in three fragmented pieces (Fig. 6) in Dhar, Madhya Pradesh[65]. The pillar fell and was split into pieces while being transported from Dhar to Gujarat. In ancient India and throughout the world, the Dhar Iron Pillar has been acclaimed as being the tallest pillar of its kind. This pillar was also composed of wrought iron and was built as a Vijaya Stambha (pillar of victory) by King Bhoja (c. 1010-1053 CE)[63]. The Dhar Iron Pillar was made using forge-welding method[66]. Both the Dhar and Delhi Iron Pillars appear to be manufactured using the similar method of welding together numerous small bloomer products. The chemical compositions (in wt%) of this Iron Pillar, was reported by Ray *et al.*[64], as presented in Table 1.

Wootz steel in Damascus Sword

Damascus sword became renowned for its impressive flexibility, outstanding mechanical

Fig. 5 — Iron beams placed in Konark's Sun Temple at Konark. Reproduced under a Creative Commons Attribution-Share Alike 4.0 International license

Fig. 6 — Three pieces of Dhar Iron Pillar lying horizontally on concrete supports, reproduced under a Creative Commons Attribution-Share Alike 4.0 International license

strength, unique surface texture, and extremely sharp cutting edge[67]. Damascus steel swords were used by soldiers all over the world and are still regarded to be among the finest swords ever made. These swords are often referred to as Damascus not because they were originated in Damascus, Syria, but owing to its distinct surface design known as the damascene or damask pattern[68]. In Arabic, the word "Damas" translates to water, which is why the wavy, water-like design on the surface of these swords is referred to as the damascene pattern.

The damascene surface pattern is a distinctive metallurgical microstructure[69] which emerges due to the alignment of Fe_3C (cementite) particles that form in wootz steel. Wootz steel, made by combining iron with 1-2% carbon[67], was the key material used to make the famous Damascus swords. This exceptional steel, admired globally, showcases impressive expertise and legacy of India in steelmaking. The word “Wootz steel” had its origin probably in the Kannada and Telugu word for steel “ukku”[67]. The damask pattern on the wootz steel is shown in (Fig. 7). In 1912, R. Hadfield[57] examined crucible steel from Sri Lanka and noted that “Indian wootz steel” was far better than the steel previously produced in Europe. Wootz steel was being produced in various regions of India and exported to the Western world even as early as 700 BCE, where it was utilized for manufacturing the renowned Damascus swords[13]. The process for manufacturing Damascus swords, as described by Sherby and Wadsworth (1985)[70], involves a sequence of steps including casting, forging, and heat treatment.

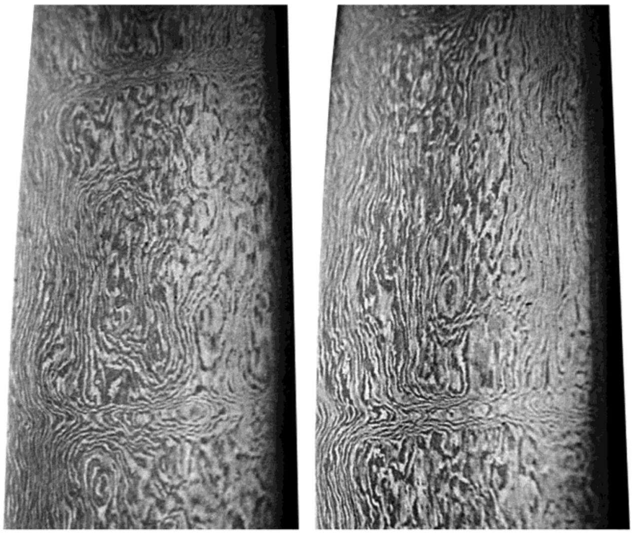


Fig. 7 — Damask pattern on the *Wootz* Steel reproduced with permission under GNU Free Documentation License (Wikimedia Commons)

India’s iron and steel industry

India, one of Asia’s fastest-growing nations, has seen its Gross Domestic Product (GDP) expand over six times since the early 1990s[71]. A major driver of this economic progress is the steel industry, positioning India as a prominent global center for steel manufacturing. Currently, it holds the position of the second largest steel producer worldwide, accounting for about 5% of global production[71]. The steel industry plays a vital role in the country’s industrial growth and is a key focus for the Government of India, as outlined in the 2017 National Steel Policy[72]. In 2019-20, India produced roughly 111 million tonnes of crude steel and this is expected to rise to 227 million tonnes by 2030, 347 million tonnes by 2040, and 489 million tonnes by 2050[73]. India has a glorious history of steel production dating back to over 100 years. The iron and steel industry in India stands as a key testament to its industrial advancement. The first “iron and steel industry” in India was set up by “Tata Iron and Steel Company (TISCO)” in Jamshedpur, marking the new beginning of a wonderful era. Tata Steel was founded in 1907 by the visionary Jamsetji Nusserwanji Tata. The company started producing pig iron in 1911 with its first blast furnace[74]. Over time, it has grown and added several facilities, creating a fully integrated steel manufacturing setup. This includes raw materials mining and processing, iron and steel making, and various other manufacturing facilities and services. One of Tata Steel's significant strengths was its access to captive sources of essential raw materials, including iron ore, coal, and limestone. The company started to harness its unutilized iron ore deposits at Joda (Orissa)[74]. Started in the early 1990s, it has been established as the primary source of iron ore.

Scientific and analytical analysis of iron samples

Ancient iron-based artifacts can provide valuable insight about fabrication procedures, corrosion behavior and other characteristics of iron used in historical times. In 2018, Vandana *et al.*[75] performed a study on the corrosion resistant ancient Indian iron artefact of Indian origin and it was aged as 2400-year-old *i.e.*, sickle blade excavated from Hastinapur (Meerut, Uttar Pradesh). Various characterizations such as scanning electron microscopy (SEM) associated with energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD) were performed for excavated sample to reveal its surface morphology, chemical analysis and corrosion resistant behavior. The sickle blade-a hand implement designed for cutting grass and harvesting crops-was in use nearly 800 years prior to the construction of the Delhi Iron Pillar and exhibits comparable microstructural features and elemental composition. It was found that the sickle blade consists of high purity iron (~92%) along with the significant phosphorus content (0.15-0.41 wt%) and slag particles (fayalite) having a chemical formula of Fe_2SiO_4. The high phosphorus content is likely to contribute to the corrosion resistance by forming a protective passive film. The absence of iron oxide and iron oxyhydroxide phases further supports the blade's excellent state of preservation.

In 2019, a study was performed in which XRD, optical microscopy, SEM were employed to examine a plowshare excavated from Ganwaria, Uttar Pradesh, India[76]. The investigation primarily aimed to identify the alloy type, analyze slag inclusions, and understand the corrosion behavior. The XRD analysis revealed the presence of α-iron as main phase. The microstructure consists of ferrite and pearlite grains, softer as compared to pearlite. Low-magnification optical microscopy revealed directionally aligned slag inclusions, indicating the use of forge welding in the artifact's production. Microstructural examination further confirmed that the plowshare was composed of carbon steel. The SEM and X-ray mapping identified the entrapped slag inclusions as SiO_2 and MgO. Additionally, on the surface, corrosion products were identified as goethite and lepidocrocite. Dwivedi *et al.*[22] carried out the same type of research in 2021, investigating experimentally some iron samples gathered from the Agaria tribe and studied its superlative corrosion resistance behavior. The samples were collected from central India (Aamadandh, Korba district, Chhattisgarh). The iron specimen was produced through traditional techniques, notably using a bloomery furnace. The design and construction of such a furnace were extensively documented by Julef *et al.*[77] in 1996. The field-emission scanning electron microscopy (FESEM) identified flake-like structures and a corrosion layer on the iron artifacts, featuring cracks of 4-5 µm range. Grazing incidence XRD and neutron diffraction techniques revealed that this layer primarily consisted of maghemite, hematite, and slag. The EDS analysis showed the rust layer contained elements such as C, Fe, Si, O, and Ca, with slag inclusions displaying non-uniform diffusion of Fe, Si, Al, Ti, O and Ca. STEM-EDS analysis identified the presence of calcium and phosphorus within the slag, along with titanium, which originated from the iron ore used during extraction, likely contributed to passive film formation, enhancing the corrosion resistance of Agaria iron.

Microstructural and compositional analysis of iron artifacts from Ambal and Vallam in Tamil Nadu[78] indicate that the axe, a cutting implement, was produced using a heat-treatment technique that employed high-carbon steel. Iron (Fe) was identified as the primary element by X-ray fluorescence (XRF) analysis, with carbon (C) and phosphorus (P) serving as significant alloying components. Additionally, Na, Cl and Ca are detected as minor impurities. Unburnt charcoal and residual slag were observed on the engraved surface of the axe-carved specimen. Iron artifacts from Junnar, Maharashtra, dated to 176 BCE-20 CE, were analyzed[79] and found to primarily consist of high-carbon steel (0.7-1.6%) with a uniform microstructure featuring small carbide particles. The presence of trace elements such as silicon (Si), manganese (Mn), and sulfur (S) in certain samples suggests that the artifacts composed of Indian steel-making crucibles.

A study by Danielowska *et al.*[80] examined the mineral and chemical composition as well as iron compounds in furnace hearth slags formed during the combustion of hard coal. Slag samples were collected from both heat and power plants and individual home furnaces equipped with grate firings. Analytical techniques including XRD, Mössbauer spectroscopy, SEM, and inductively coupled plasma (ICP) analysis were utilized. The primary constituents of furnace hearth slags were found to be SiO_2, Al_2O_3 and Fe_2O_3. XRD analysis reveals that mullite and quartz are the predominant phases present in the furnace hearth slags. The study also revealed significant variations in the concentrations of toxic elements, including Cr, Cd, Ni, Pb, Tl, Zn, Ba, As, and Cu, as well as Fe, depending on the slag's source.

The more comprehensive review on chemistry of ancient iron materials in India was given by Agasti and Pani[55] in which they focused on the ancient materials obtained across India through the lens of different characterization techniques including XRD, FTIR, EDS, Mossbauer spectroscopy, PIXE, SEM, TEM, etc. to reveal the synthesis process, surface morphology, chemical composition, and the factors contributing to the distinctive features of iron artefacts.

Current challenges and future prospective

The research area on ancient Indian iron has the ability to enlighten and inspire the young minds to develop new materials and technologies. The ancient Indians, for example, devised procedures for producing high-quality steel from recycled iron, which may be applied today to produce more sustainable and ecologically friendly steelmaking processes. Furthermore, the study of ancient Indian ironworking may also provide insight into the development of new alloys or more effective iron smelting technologies. One of the potential fields of research is the development of new iron alloys that are lighter, stronger and more corrosion resistant than conventional steels. Ancient ironworkers in India developed a number of unique alloys including Wootz Steel, which was famous for their exceptional characteristics. The development of more efficient iron smelting processes is another interesting field of research. Although the ancient Indians employed a variety of iron smelting procedures, but many of them were ineffective and produced a lot of waste. The researchers may be able to discover new strategies for producing less waste by analyzing historical iron smelting procedures. Overall, research into ancient Indian iron metallurgy has the potential to make substantial contributions to the production of new materials and technologies, as well as archaeology and conservation. Thus, by learning from the wisdom of past, we can move towards a more sustainable and technologically advanced future. However, this initiative encounters several contemporary challenges; chief among is the inherent scarcity and preservation issues associated with the archaeological evidences, complicating the reconstruction of ancient ironworking techniques. In addition, it is not possible to extract the iron from well known Indian iron monuments, for instance, Delhi Iron Pillar, in order to analyze its properties and the mechanism behind its formation as these are archaeologically protected monuments. Therefore, searching for ancient iron working places and the tribes who were involved in iron making practices can be a fruitful approach to this problem.

Conclusion

The present review underscores the profound significance of India's rich heritage in the realm of Iron metallurgy. From the inception of the Iron Age to the time-tested methods documented in ancient Indian literature, the journey of iron metallurgy in this region has not only paved the way for technological advancements but also established a cultural legacy. The ancient Indians were true masters of iron metallurgy, and their skills and knowledge were passed down from generation to generation for centuries. This article highlights the evolution of iron metallurgy in ancient India along with early iron working and its time frame and also the existence of iron in ancient Indian literature. Notable examples such as Iron Pillar in Delhi, Iron beams at Konark Sun Temple, Dhar Iron Pillar, and swords made of Damascus steel have been presented, which showcase impressive craftsmanship of ancient Indian metallurgists, leaving an enduring mark on the country’s technological heritage and cultural history. Furthermore, the rise of steel industry of India has also been highlighted. The timeless wisdom embedded in India's ironworking heritage can illuminate a path towards a more sustainable and technologically advanced future. By bridging the ancient and modern worlds, we can learn from the innovations of the past and apply them to the challenges of the present.

Acknowledgements

S.D. acknowledges the financial support from Indian Knowledge Systems (IKS), AICTE, New Delhi, India in the form of junior research fellowship (JRF) under IKS Research Projects Scheme via grant no. 2-23/AICTE/IKSBGSI/Research Project/2022-23/31. The authors M.K.K, S.D. and P.K.D. are grateful to Ultra International India Pvt. Ltd., Ghaziabad, India for providing the lab furniture for Renewable Energy Laboratory at SPS, JNU.

Conflicts of Interest

There are no conflicts to declare.

Author Contributions

SD-investigation; formal analysis; methodology and writing – original draft; PKD: investigation; formal analysis; methodology and writing-original draft; SK: investigation; resources; validation; writing – review & editing; VT: formal analysis; methodology and writing – original draft; BKP: conceptualization; resources; supervision; validation and writing – review & editing; MKK: conceptualization; resources; supervision; validation and writing – review & editing.

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