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ARTICLE

A critical review on wootz steel of India

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Abstract

This paper critically reviews wootz steel, an ancient high-carbon steel renowned in ancient India, focusing on its unique qualities, production process, and historical significance. Known as crucible or Damascus steel, wootz steel boasts extraordinary mechanical strength, superior cutting ability, and distinctive surface patterns, captivating scholars and metallurgists for centuries. Its metallurgical properties and historical importance highlight its role as a symbol of technological prowess and craftsmanship in ancient Indian metallurgy. Wootz steel also held cultural value, often associated with status and prestige. The advanced fabrication techniques employed by ancient Indian metallurgists showcase their expertise in heat treatment processes. The meticulous craftsmanship involved in creating wootz steel highlights the ingenuity and dedication of ancient metallurgists in mastering the art of metallurgy. This work aims to enrich our understanding of India's technical heritage and acknowledge the remarkable achievements of past Indian civilizations. It seeks to inspire future innovations in metallurgy by uncovering lessons from the history and metallurgy of wootz steel. Retrospection on ancient materials and techniques offers insights that can refine modern manufacturing processes and materials engineering. This comprehensive review hopes to preserve and carry forward the legacy of wootz steel, ensuring its significance endures for future generations.

Keywords Indian knowledge system · Wootz steel · Damascus blade · CNTs · Archeometallurgy

1 Introduction

India has a rich history and heritage of excellence in its knowledge base, dating back to ancient times. The extraordinary metalworking and efficacy in metallurgy have been present since the Copper Age, as evidenced by excavations of Indus-Saraswati Civilization sites (Tripathi, 2018, pp. 279–295). The intellect in metalworking has continued in ancient India. The greatest height of this efficacy was achieved in the Iron Age. The living evidence of these extraordinary metallurgical skills can be seen in the iron pillars of Dhar and Delhi, the iron beams of the Konark Sun Temple, and numerous forge-welded guns and cannons of India that were in use until the late 1700s (Agasti & Pani, 2023, pp. 1–17). One of the greatest metallurgical marvels of ancient India was wootz steel. Wootz steel has captivated researchers, historians, and metallurgists for centuries (Sharada & Srinivasa, 2004, pp. 1–146). Wootz steel, which originated from the southern part of India was a type of high-carbon steel. This gained fame due to its exceptional properties and distinctive damask pattern visible on the surface (Ranganathan & Srinivasan, 2006, pp. 67–77). The uniqueness of wootz steel lies not only in its aesthetic appeal but also in its exceptional cutting ability and edge retention, which were historically noted to surpass those of contemporary European blades, particularly in accounts from 12th-century Crusaders, which were quite fascinating to the metallurgist even in modern times (Wadsworth, 2015, pp. 1–7).

Wootz steel is a high-carbon steel that is highly regarded for its unique microstructure and exceptional hardness (Wadsworth & Sherby, 1997, pp. 1–42). This extraordinary variant of steel, far ahead of its time, was extensively traded across various regions even before the foundation of modern steel-making methods. The significance of wootz steel in the field of metallurgy is evidenced by its widespread use and demand (Desai, 2018, pp. 926–944). Arguably the

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most notable application of wootz steel was in the crafting of the well-famed Damascus blades during the Middle Ages. These blades were a testament to the superior quality of wootz steel. These blades are highly valued for their efficacy in terms of toughness and cutting ability. The pattern, a direct result of the steel's special microstructure, introduced the aesthetic appeal to these blades, further enhancing their value (Papadatu et al., 2023a, pp. 871–886). The microstructure of wootz steel is quite unique and complex, and characterized by its pattern of bands of micro-scale carbides distributed within a predominantly pearlite matrix (Verhoeven, 2000, pp. 286–296). This intricate configuration contributes significantly to the steel's exceptional hardness and strength (Sherby & Wadsworth, 2001, pp. 347–353). The unique microstructure sets wootz steel apart from other types of steel.

In a strange turn of events, the method of fabricating wootz steel was lost around the seventeenth century. The disappearance of this knowledge was a significant loss to the world of metallurgy. However, it sparked a curiosity among researchers and historians, leading to extensive studies and research aimed at understanding and possibly recreating this ancient technique. The quest to unlock the secrets of wootz steel production continues to this day. Despite the loss of its fabrication method, the influence of wootz steel in the field of metallurgy is undeniable and far-reaching. Its unique properties, coupled with the enigma surrounding its production, continue to captivate the interest of scholars across the globe. This enduring interest makes wootz steel a significant subject of study in the exploration of ancient metallurgical techniques. The story of wootz steel serves as a reminder of ancient technological advancements and the importance of preserving knowledge for future generations. As research continues, it is hoped that the secrets of this ancient marvel will be unraveled and perhaps even the lost art of producing wootz steel will be revived.

This comprehensive paper examined the metallurgical techniques employed in the production of wootz steel. This study aims not only to provide a deeper understanding of the unique properties of wootz steel but also to shed light on its historical significance. Specifically, an investigation into the advanced metallurgical methods used by ancient Indians in creating this superior variant of steel. These techniques, far ahead of their time, set the foundation for what would eventually become a groundbreaking innovation in the field of metallurgy. The archaeological findings, including artifacts and production sites, provide tangible proof of the existence and use of wootz steel in ancient times (Girbal, 2017, pp. 1–997). The examination of these historical remnants would provide a better understanding of the techniques used, the scale of production of this remarkable steel. The ultimate aim of this exploration is not only to understand the past but also to contribute to the ongoing research in this field. By studying wootz steel and the techniques used in its production, it can be added to existing knowledge in the field of metallurgy. This could potentially inspire future innovations and advancements in steel-making processes. This paper, therefore, is not merely an investigation into a specific type of steel, but a journey into the past, tracing the genesis of a metallurgical marvel that continues to fascinate scholars and researchers to this day. The study of this ancient marvel offers valuable lessons for the future, emphasizing the importance of preserving and understanding our technological heritage. The investigation into wootz steel forms a part of the larger narrative of human advancement and innovation, reminding us of the importance of understanding and preserving our past to inspire and inform our future. As such, the continuing research into this ancient steel variant holds the potential to unlock new innovations and deepen our understanding of the rich tapestry of human technological advancement.

2 Historical context of wootz steel

The origin of wootz steel can be traced back to India, with evidence dating back to 300 BCE. The term “wootz,” signifying a special type of steel, has its roots in a Kannada word, “ukku,” meaning steel, which was anglicized by European traders. The historical advances in wootz steel in chronological order has been presented in Table 1. The chronology presented in Table 1 establishes India as a pioneer of wootz steel production.

Several authors have discussed the historical context of wootz steel. Jaikishian et al. (2021, pp. 15–23) investigated the ingots found from excavation in Konasamudram, Telangana. The wootz ingots were found to be uniform in shape, size, weight, and geometrical dimensions, indicating large-scale batch production of wootz steel in that locality. The history and significance of India's wootz steel have been presented in the works of Sharada and Srinivasa (2004, pp. 1–146). The study highlights instances of technology transfer from the East to the West, leading to discoveries such as Bessemer iron. The attempt to replicate wootz steel's fine structures may have contributed to the discovery of carbon steel in the West. In an article in Nature (“Damascene Steel and Modern Tool Steel”, 1921, pp. 248–249), Damascene steel has been compared with modern tool steel. The comparisons highlight the significance of breaking and evenly distributing carbides during forging. Metallographic examinations have been conducted to investigate the distribution of carbide particles. Key discoveries include the structural and property similarities between Damascene steel and high-speed tool steel, the classification of Damascene steel within the hypereutectoid series of carbon steels, and the structural

Table 1 Chorological accounts on the history of wootz steel

References	Event	Time frame
Desai et al. (2023, pp. 1–14)	Initial discoveries include crucibles and high-carbon artifacts unearthed from the megalithic and Iron Age periods in southern India. These findings hint at the potential production of semi-solid or molten steel using the crucible method, possibly marking the earliest instance of such steelmaking in history	300 BCE
Moore (1834, pp. 1–192)	King Porus presents Alexander the Great with *ferrum candidum*, also known as "bright iron."	323 BCE
Park and Shinde (2013, pp. 3991–3998)	Wootz steel was primarily used as an everyday work material	200 BCE
Lang (2017, pp. 57–70)	Europe developed a fire-welding technique for crafting iron weapons with steel cutting edges	100 BCE
Gilmour (2017, pp. 57–70)	The emergence of pattern-welded steel featuring twist and unique chevron patterns occurred in Europe	100 CE
Jones (1997, pp. 7–11)	Pattern-welded steels were utilized by the Merovingians and Carolingians in Europe	500 CE
Fedrigo et al. (2018, pp. 1249–1263)	Use of pattern welded steels by Vikings	800 CE
Feuerbach (2002, pp 1–355)	Production of crucible steel spreads to Merv in Central Asia	900 CE
Purwanto et al. (2021, pp. 397–410)	Kris, the pattern welded swords were made in Indonesia	900–1000 CE
Nicolle (2008, p. 212)	During the Crusades, Europeans are impressed by the superior craftsmanship of the Damascus Sword	1095–1270 CE
Sherby et al. (1985, pp. 112–120)	Saladin, the Saracen warrior from Egypt, showcases the Damascus sword made of wootz steel to Richard the Lionheart, the King of England	1100 CE
Williams (2012, pp. 1–299)	Decline in use of pattern-welded blades	1400 CE
Sherby et al. (2001, pp. 347–353)	Russian blacksmith made '*bulat steel*'	1500 CE

resemblance between annealed high-speed tool steel and Damascene steel.

Srinivasan (1994, pp. 49–59) has analyzed the archaeological evidence of crucible wootz steel production at the Mel-Siruvalur site in the South Arcot district, Tamil Nadu. Rigorous metallurgical experimentation confirmed that there was a production center for wootz crucible steel in the Deccan. The importance of materials science in investigating the properties and evolution of wootz steel in the latter half of the twentieth century has been discussed in the works of Ranganathan and Srinivasan (2006, pp. 67–77). The authors explored the historical and metallurgical significance of wootz steel, underscoring the contributions of Indian metallurgists. They have explored the collaboration between John Verhoeven and Alan Pendray in modern Damascus blade production, focusing on banded structures and the utilization of vanadium. Furthermore, they underscored the role of materials science in understanding the properties of wootz steel and its impact on the field's advancement, referencing the establishment of the iron-carbon phase diagram and the importance of modeling and design.

Srinivasan and Griffiths (1997, pp. 111–125) conducted preliminary surveys on crucible fragments from Mel-Siruvalur. The works indicate that the crucibles are associated with steel manufacturing. They were discovered stacked in a furnace close to iron production areas and possess a consistent pearlitic structure made of high-carbon hypereutectoid steel. The method entails carburizing molten low-carbon iron in crucibles filled with carbonaceous material. Crucible composition appears uniform across various locations. Mapping and sampling of the slag heap along with the examination and analysis of ores, slags, and iron fragments in Ghattihosahalli, Karnataka, has been presented by Anantharmu et al. (1999, pp. 13–25). The authors indicate that Ghattihosahalli was a center for iron and steelmaking in the nineteenth century. Crucible steel was manufactured in Ghattihosahalli in the late nineteenth century. The slag heap and furnace remains in Ghattihosahalli are significant.

The technology, chronology, and role of crucible steel have been discussed by Park and Shinde (2013, pp. 3991–3998). The paper argues that wootz steel was primarily used as a work material in everyday use. The paper suggests that the origin of crucible steel may trace back to the second century CE. The review of literary and historical sources regarding wootz steel, analyzing its composition, microstructure, and mechanical properties, has been presented by Srinivasan and Ranganathan (1997, pp. 69–82). The paper reviews the development and properties of ancient Indian wootz steel. Wootz steel was an ultra-high carbon steel with superplastic properties. It was highly regarded and traded in ancient Europe, China, and the Middle East. The study of wootz steel influenced modern metallurgical advances. Recent experiments have reconstructed the composition and behavior of wootz steel.

The archaeometallurgical evidence from Mel-Siruvalur, Tamil Nadu, India, demonstrating the production of ultra-high carbon, hyper-eutectoid steel via molten carburization of wrought iron in crucibles, has been discussed in the works of Srinivasan (2017, pp. 909–915). The author reports that during the nineteenth century, various crucible steelmaking methods in India were documented by travelers and observers, such as the Deccani, Mysore, and Tamil Nadu processes. At the Mel-Siruvalur site, remnants of broken crucibles strongly indicate the production of high-carbon hypereutectoid steel through molten carburization of wrought iron. The crucible's composition, rich in silicon and carbon, suggests its high resistance to heat. Analysis of crucible fragments revealed microscopic metallic prills with characteristics of ultra-high carbon hypereutectoid steel. The presence of equiaxed honeycomb-shaped prior austenite grains, lamellar pearlite eutectoid, and pro-eutectoid cementite indicated the formation of ultra-high carbon steel. The absence of cast iron remnants and the presence of carbon-rich material in the crucible fabric suggest that carburization of wrought iron was used to produce ultra-high carbon steel. These findings suggest that the crucible steelmaking process, commonly referred to as the 'Tamil Nadu process,' may be older or more primitive than the co-fusion method.

Radiocarbon dating of high-carbon crucible steel samples from Telangana, India, has been done by Desai et al. (2023, pp. 1–14). The radiocarbon dating of the steel samples yielded a wide range of dates. Several factors could have influenced the isotopic composition during sample preparation. The dates span from 300 BCE. The samples are categorized into three groups: Konapuram, Konasamudram, and Telangana. Repeat analyses of the same object consistently produced similar radiocarbon ages. It is crucial to reassess assumptions and meticulously examine sampling and measurement procedures. Possible contributors to these unexpected results include production methods, raw materials, and contamination.

Feuerbach (2002, pp. 1–355) describes the origin, use, and production of crucible steel. The author indicates that crucible steel, typically linked with Indian/Sri Lankan origins (known as wootz), was not exclusive to those regions but was also crafted in Central Asia using a distinctive technique. Studies of materials unearthed from sites such as Merv, Turkmenistan, along with the scrutiny of blades from various Central Asian areas, have unveiled unique traits similar to those found in ancient crucible steel artifacts. These traits encompass diverse patterns and formations of cementite, reminiscent of historical crucible steel. This revelation suggests that crucible steel was present in Central Asia for over 1500 years, as evidenced by the identification of blades with Damascus patterns.

Srinivasan (2013, pp. 83–90) discussed South Indian iron workings, with a focus on wootz steel, through the analysis of smelting debris and scanning electron microscopy (SEM) of wootz steel. The results show a vitrified crucible fragment alongside iron smelting remnants at Kodumanal. An elemental distribution map illustrates iron content within the crucible fragment from Kodumanal. Examination of the microstructure of high-carbon wootz steel retrieved from crucibles unearthed at Mel-siruvalur. Microscopic analysis of a nail originating from early historic Pattanam, Kerala, reveals the distinctive structure of wootz steel.

The early instance of crucible steel has been described in the works of Craddock et al. (1998, pp. 7–14). The study utilizes artifacts from the British Museum's holdings and assesses their significance in light of recent discoveries in the early history of crucible steel. The primary discoveries include the examination of a Sasanian sword dating back to the sixth-seventh century CE, showcasing crucible steel. This finding hints at the broader and earlier utilization of crucible steel than previously believed. Rehren and Papachristou (2003, pp. 393–404) conduct a comprehensive comparison and analysis of archaeological findings regarding crucible steel production in Central Asia and the Indian subcontinent. It examines the ceramic tradition and its historical evolution in distinct regions, as well as the metallurgical techniques employed. It indicates disparities in crucible steel production between Central Asia and the Indian subcontinent, encompassing differences in ceramic tradition, vessel attributes, and historical progression. Furthermore, it notes variations in the metallurgical processes utilized for steel-making operations across these regions.

The exploration of iron and Damascus steels from the perspective of ancient blacksmiths to unveil their artistic achievements and pivotal role in early material concepts has been explored in the works of Sherby and Wadsworth (2001, pp. 347–353). The paper examines the methods used to comprehend the behavior of iron and Damascus steel, emphasizing the historical significance and blacksmith expertise in deciphering the iron-carbon phase diagram. It highlights Damascus and Japanese steel swords as exemplary feats, celebrated for their cutting precision, durability, and intricate patterns. Damascus steels, classified as ultra-high carbon steels (UHCSs), boast carbon content ranging from 1.0 to 2.1%, with modern metallurgical insights revealing their remarkable properties. The study emphasizes the value of ancient metallurgy in understanding societal development, with traditional blacksmithing insights informing contemporary material processes. Notably, the potential for ultrahigh-strength wires from cold-drawn pearlitic structures in UHCSs is examined; however, practical implementation depends on cost-effective processing methods, such as continuous casting and mechanical working.

Wadsworth (2015, pp. 1–7) explored the archeometallurgy related to swords. The paper reported the evolution of layered steels in swords, tracing historical advancements and showcasing examples like Chinese pattern-welded blades and Japanese *katanas*. It summarizes carbon dating findings on iron-based artifacts, highlighting the importance of swords in studying technology and societies of the pre-firearms era. Archaeologically, swords assist in dating through carbon analysis. Advanced materials, such as Damascus steel, played a crucial role; however, challenges like contamination and forgery underscore the necessity for meticulous scrutiny.

Feuerbach (2008, pp. 53–57) introspected the history of crucible Damascus steel identifying the culture involved in its production, trades, and applications. It challenges prevailing accounts by providing evidence that prompts a reevaluation of the origins of this steel and its importance to warriors. Initially, "Damascus steel" referred to blades that showcased the unique crucible Damascus pattern; however, its definition became blurred with the introduction of pattern-welded varieties in the eighteenth century. The water pattern found on these blades held religious significance in Islamic areas, symbolizing the waters of Paradise, and was highly prized. The study suggests that variations in the water pattern may result from disparities in the solidification rate of the crucible steel ingot, which could be influenced by religious beliefs and customs.

A field survey conducted in Northern Telangana aimed to analyze smelting technologies and variations in the identification of different traditions in crucible steel-making was performed by Juleff et al. (2014, pp. 1030–1037). Data were collected from field diaries, GPS devices, and photographs, focusing on smelting technologies and variations in crucible steel-making traditions. The survey recorded 245 locations, with 183 linked to primary iron smelting and around 20% associated with crucible steel manufacture. Variations in smelting techniques were observed, including differences in tuyere size and furnace wall construction between settlements and remote forested areas. Two distinct traditions of crucible steel-making were identified: one using small, thin-walled crucibles and the other employing large, conical-lidded crucibles. The survey aimed to characterize the archaeometallurgical landscape, focusing on understanding the nature, range, interconnections, and spatial and temporal distribution of the technologies. Data were categorized into landscapes, locations, collected materials, and ethnographies. Systematically archived datasets were cross-correlated to facilitate interpretational syntheses and reconstructions of regional technologies.

Two Islamic mirrors, one made of pure iron and the other of crucible steel, are investigated by Craddock and Lang (2021, pp. 35–46), provide details about steel production and mirror crafting methods. Metallographic analysis of a 14th-century Islamic mirror suggests it was likely made of crucible steel, indicating in situ carburization and co-fusion processes. The examination confirms that mirrors were indeed made of steel, as mentioned in historical records. Recent research has broadened the understanding of crucible steel's usage, including its application in various artifacts, such as mirrors. Analysis of the 14th-century mirror reveals a microstructure consistent with crucible steel, with approximately 0.7–0.8% carbon content. Crucible steel's ability to maintain a brilliant, reflective surface was highly valued historically, and it was even utilized in 18th-century Europe for imitating diamonds.

Desai (2018, pp. 926–944) presented an overview of archeometallurgy related to crucible steel. The discussion extends to exploring the potential application of these methods in studying crucible steel in India, with an interest in investigating its origins and manufacturing processes. The study examines the formation of crucible steel ingots from ore, aiming to understand the composition and production techniques involved. Promising data on crucible steel and associated materials have emerged from studies in Sri Lanka, Iran, and the Baltic Sea-Iranian trade route, suggesting potential sources and trade routes for crucible steel production. The research indicates that speculation and preliminary analysis in the field of crucible steel can evolve into a concrete empirical methodology, offering potential for future advancements in understanding its production.

Insights from multiple disciplines, such as materials science, blacksmithing, history, and anthropology, have been presented in the works of Feuerbach (2006, pp. 48–50) to explore crucible Damascus steel production. It analyzes crucible fragments from regions such as Merv in Uzbekistan to determine their elemental composition through electron-probe microanalysis. Historical records from researchers such as George Pearson, David Mushet, and Michael Faraday are scrutinized for their studies on the properties of wootz steel. Laboratory experiments replicate the crucible Damascus steel production process using both traditional and modern methods. Crucible designs, furnace setups, charges, solidification, cooling rates, and forging techniques from various regions are compared to understand their impact on ingot and final product properties. The study explores the etymology of the term "pulad" for crucible steel in Central Asia, suggesting its origins in the Sanskrit or Avestan languages. While some insight into decorative patterns in crucible Damascus steel is gained, a complete understanding of their historical creation remains elusive. The research notes the diverse factors influencing ingots and final products, including crucible composition, furnace design, charges, and forging techniques; however, the precise effects of these factors are not fully understood. Historical variability in the quality and properties of crucible steel ingots, particularly in carbon content and trace elements, is attributed to differences in the crucible charges. The paper also highlights the global cultural impact of Indian crucible steel production, leading to the discovery of alloy steels.

The structure of three Zlatoust bulat (Damascus steel) blades, including one from 1859, was examined by Schastlivtsev et al. (2008, pp. 179–185) using transverse template analysis. It highlights the Anosov blade, crafted in 1841, made from pure carbon crucible steel, showcasing Damascus steel characteristics. Zlatoust gained fame in the nineteenth century for its functional and ornate cold arms, including cast and welded damask steel, renowned as some of the finest cold steels. Anosov, overseeing the Zlatoust factory from 1821 to 1847, not only managed arms production but also pioneered technology for producing high-quality cast (crucible) steel and "Russian bulat" (Russian Damascus steel).

The metallographic examination of Damascus steel with different compositions has been discussed in the works of Strobl and Haubner (2015, pp. 852–859). The paper investigates Damascus steels of diverse compositions using metallographic methods. While most steel layer interfaces exhibit uniformity influenced by carbon diffusion, some areas display enclosures of oxides and slag stringers due to errors in the forge welding process. Microstructures were analyzed using optical microscopy and validated by Vicker's microhardness measurements.

The analysis of Damascus steel fabrication has been presented in the work of Hammond (1983, pp. 263–269). Forging Damascus steel required precise control of temperature and strain rate to transform angular cementite platelets into equiaxed grains. This was typically conducted at temperatures between 800 and 900 °C with a slow, controlled strain rate. The result was a fine two-phase structure of iron and equiaxed cementite grains, resembling those found in superplastic titanium alloys and tin–bismuth alloys. This process yielded a ductile and forgeable steel that hardened and toughened upon cooling to room temperature.

The significance of wootz steel in the development of modern materials science has been highlighted by Srinivasan and Ranganathan (2011, pp. 1–3), authors note important milestones including the identification of steel as an iron–carbon alloy in 1774, the experimental investigations of Michael Faraday, and the establishment of the iron–carbon phase diagram in 1898, which was largely influenced by research on wootz steel. They also highlight the widespread adoption of optical microscopy due to studies on wootz steel.

The steelmaking techniques used in ancient India for producing wootz steel have been identified by Habashi (2011, p. 60) as the pioneering foundation of steel production. The author described that the use of Sorel metal, an iron-carbon alloy, led to the realization of vanadium's efficacy in producing banding of Fe_3C in high-carbon steels. Vanadium, found in ilmenite ore, was also detected in low levels in ancient wootz steel blades, suggesting its presence in Indian ore deposits used for wootz steel production. This discovery offers insights into vanadium's potential role in ancient metallurgy. Moreover, the author mentioned that the technique for crafting exceptionally hard and tough swords, known as "Damascus" swords, was introduced to Europeans by India during the Christian Crusades in the Middle East in the twelfth century.

The historical importance of Indian steel production and its profound influence on global trade routes have been emphasized by Woźniak (2016, pp. 709–726). The author discusses the importation of Seric iron from the Chera kingdom in southern India, utilized in crafting high-quality weaponry. Through microscopic analysis of slag on crucible lid fragments, crucible steel production centers were identified outside India from the third century CE, including the Deccan region. Indian ports like Musiris and Barbaricon played crucial roles as trade hubs. Archaeological evidence in Gandharan Taxila supports the existence of crucible steel weapon production, highlighting Indian steel's widespread influence in ancient trade networks. The work by Dube (2014, pp. 2390–2396) discusses the incorrect transliteration of the Sanskrit term "utsa" as "wootz" concerning Indian crucible steel. While it provides significant information on wootz steel, it does not fully clarify its properties. However, Helenus Scott is credited with introducing the term "wootz" for Indian crucible steel in 1794.

3 Wootz steel production

The archeological evidence of wootz steel production has been explored by Woźniak (2020, pp. 543–566). The study aimed to recreate ancient crucible steel production through practical experiments, thereby revealing the challenges and insights associated with this process. Among the five crucibles tested, two displayed promising signs of carburization in the metal pieces, despite incomplete melting, likely due to insufficient temperature and duration. Some crucibles cracked at the bottom, possibly due to an uneven temperature gradient. Despite these setbacks, the experiment provided valuable archaeological and ethnographic insights, underscoring the need for integrating findings across disciplines. The study highlighted the complexities of reconstructing traditional crucible steel production methods. The control of temperature while making crucible steel is necessary. The use of a gauge instrument for temperature measurement has been reported in the works of Buchanan (1829, pp. 7–16). The author mentioned an instrument for regulating furnace heat and studying high-temperature body heat, as well as thermometer scales. A discussion on the use of water circulation in tubes for temperature control in a Furnace has been presented. Furthermore, it details a method for predicting furnace heat by determining the room temperature and measuring the impact of the fire's radiant heat on the thermometer, enabling precise replication of desired temperatures.

The failed attempt to reproduce Damascus blades and the mystery behind external patterns in ordinary steel have been investigated in the works of Wilkinson (1837, pp. 187–193). The authors identified that post-processing the blade by rubbing it with wood ashes and water, coating it with a paste of chalk and water, and then immersing it in a copper sulfate solution would create the external pattern on the blade. The author concluded that etching or engraving a blade of common steel is a usual but ineffective method of imitation. Verhoeven (1987, pp. 145—151) presented a review of literature related to the production of wootz steel from bloomery iron. The author identified that the process for producing Damascus steel involved carburization. The carburizing gas in the crucibles contained significant levels of H_2. The cast cakes of wootz steel had a carbon composition of 1.6%. Crucible temperatures in the range of 1400–1450 °C were achieved in the wootz process. The presence of this H_2 gas yet to be investigated further. However, this work established a strong experimental foundation for understanding the thermochemical environment within ancient crucibles. Verhoeven provided the first modern mechanistic link between crucible chemistry and the resulting carbon gradients observed in wootz ingots by quantifying carburization parameters. The production of ancient wootz steel using crucible steel ingots has been discussed extensively (Verhoeven et al., 1996, pp. 9–22). The work indicates that wootz Damascus steel blades are meticulously crafted by forging small ingots in a gas-fired furnace, resulting in a distinctive surface pattern similar to banded hypoeutectoid steels, characterized by aligned cementite bands. Thermal cycling during forging selectively enlarges cementite particles, which is aided by the addition of carbide-forming elements such as V, Cr, and Ti. The work is pivotal because it transitions from descriptive observation to a causal explanation—showing that trace carbide-forming elements, particularly vanadium, govern the alignment of cementite bands. It effectively demonstrates that the Damascus pattern is not a mysterious artifact but a predictable outcome of microalloying and thermal processing. Achieving aligned cementite bands is improved by avoiding domed ingots, controlling impurity levels (S and P), and precisely adjusting carbide-forming element concentrations. The formation of these bands is linked to microporosity within the ingots, which is eliminated during high-temperature forging. In another work, Verhoeven (2001, pp. 62–67) discusses the pattern formation mechanism while producing wootz steel. The ladder pattern on the Damascus blade results from crosswise grooves, while the rose pattern forms through shallow hole drilling. Frozen impurity atoms form a lattice amidst dendrites, aided by multiple heating and cooling cycles, promoting cementite particle growth. Micro-segregation during solidification generates the distinct surface patterns. The photograph of a reproduced wootz Damascus blade, displaying the intricate Damascene surface design featuring both the ladder and rose patterns intertwined, is shown in Fig. 1.

Fig. 1 Reconstructed wootz steel blade [reproduced with permission from Verhoeven et al. (1998, pp. 58–64) © 1998 The Minerals, Metals & Materials Society]

Sharada and Srinivasa (2004, pp. 1–146) have discussed the production process of wootz steel. The authors identified that production involved carburizing wrought iron from bloomery ingots, which were packed into crucibles and fired over long cycles (12–14 h) using charcoal. The reproduction of ancient wootz steel has been attempted in the works of Perttula (2001, pp. 65–68). The reproduced wootz steel blade has been compared with the microstructure and cutting test with an ancient blade. The process followed was heating the bloomery ingots to 940 °C to dissolve cementite and retain carbides, followed by slow cooling to nucleate cementite and transform matrix into pearlite. Perttula's findings critically validate the Verhoeven–Pendray model. By matching mechanical properties and microstructure between the reproduced and historical blades, the study confirms that the so-called 'lost' Damascus process is experimentally reproducible. The pattern has been indicated by air induction melting of pure iron with additions of graphite, ferrochromium, and ferromanganese. The toughness and strength have been enhanced by reheating ingots at 1140 °C and subsequent water immersion, followed by air cooling. The reproduced blade has a similar composition and microstructure, along with improved cutting ability, when compared with the ancient blade. The author also emphasizes the effect of slow cooling and thermal cycling on generating the damask pattern. Verhoeven and Pendray (1992, pp. 195–212) experimented with the reproduction of Damascus steel blades using Wordsworth and Sherby's method, forging the small ingots together. They concluded that replication at the microstructural level has failed by the first method. However, the second method, employing small steel ingots resembling authentic blades, effectively resolved challenges such as severe hot shortness and graphitization during forging. This resulted in forged blades with closely matched patterns and microstructures.

Sukhanov (2023, pp. 1481–1493) aimed to replicate the Damascus steel structure in laboratory settings using contemporary analogues of high-carbon steels and alloys. High-carbon alloys with reduced impurity levels were utilized to recreate the Damascus structure. These alloys underwent crucible melting via an induction furnace in a nitrogen atmosphere. Subsequent forging employed a pneumatic hammer with 150 kg falling parts, with intermediate heating conducted in a forging furnace. Intermediate heating temperatures for forging remained below 950 °C, with a minimum holding time of 15 min. Sukhanov's work adds independent confirmation of the Verhoeven–Pendray mechanism. His results underscore that the characteristic banded microstructure can emerge in pure systems, provided that forging parameters and microalloying are carefully controlled. This comparative evidence closes a major gap between historical replication and modern materials science understanding.

A technique replicating the intricate microstructures characteristic of authentic Damascus blades was developed by Verhoeven (2002, pp. 356–365). The author utilized controlled impurity levels and a specialized heat treatment process on hypereutectoid steels. By forging ingots composed of a mixture of pure iron and Fe–4–C alloy, known as Sorel iron, and then subjecting them to controlled thermal cycling, the desired alignment of microstructures was successfully achieved.

Strobl et al. (2017, pp. 333–340) experimented with the replication of an 8th-century Damascus sword blade. The replication process begins by stacking and securing iron and C45 steel plates, which are then heated and forged into a rod. This rod is cut, stacked, heated, and forged again to create 27 layers, forming the twisted Damascus steel. After twisting and grinding, the steel is shaped to a thickness of 6 mm, revealing the Damascus pattern. A 650 × 20 × 10 mm rod is forged for the blade's core, with one half forged to accommodate the twisted steel inlays. The core and inlays are fused through forging, followed by heat treatment and intense grinding to achieve the final sword shape, with Damascus markings revealed by etching.

The creation of Damascus steel, which began with the casting of ultrahigh-carbon steel, such as wootz, in Indian foundries, was discussed by Sherby and Wadsworth (1985, pp. 112–120). This steel is made by reducing iron ore with charcoal, followed by hammering wrought iron to remove impurities and increase the carbon content. The steel is heated to over 1000 °C, air-cooled to around 800 °C, and then quenched in a warm brine-like solution. Forging the steel disperses cementite and shapes the surface pattern. In lab tests, the casting is rolled as it cools, mimicking the effect of forging. The authors simulated forging effects on Damascus steels, enhancing toughness and reducing brittleness. The microstructure resembled that of Damascus steels, exhibiting a visible damask pattern after acid etching.

Maryon (1960, pp. 52–60) reported that the Damascene process in Western Europe for sword blades differs from that in Syria, Persia, and India. In the West, it involves pattern-welding and constructing composite strips of iron and steel, while in the East, it focuses on the composition and heat treatment of cast steel billets. The fine watered pattern in Damascene swords results from the controlled crystallization of carbon-rich steel, slowly cooled and forged at a cherry-red heat. The Kirk Narduban pattern is highly valued, with Oriental connoisseurs preferring darker, etched shades, which are seen as superior in quality. Ores used at Kona Samudram included local magnetic schist, haematite, ferruginous sands, and quartzites. Swordsmiths and dealers kept the process's difficulties secret, maintaining a serious demeanor when discussing them with customers.

Balasubramanian (2020, p. 685) recently reported an additive manufacturing (AM) method to recreate wootz steel. Using directed energy deposition (DED) with an Fe19Ni5Ti alloy and Intrinsic Heat Treatment (IHT), the study aimed to mimic the Damascus pattern. Results showed that IHT during the AM process enabled in situ control of the microstructure layer by layer, producing a steel with locally adjustable properties. The newly engineered Fe19Ni5Ti alloy exhibited improved mechanical properties, achieving strength and elongation comparable to those of conventional steels.

The process of producing Damascus steel, which originated in ancient India around 300 BCE and later gained global recognition, was documented by Prakash (2001, pp. 52–91). It was crafted through carburizing wrought iron in a sealed crucible or decarburizing white cast iron with synthetic slag. Despite the distinct Damask pattern, the exact forging method responsible for creating this texture remains a mystery. Kobasko (2011, pp. 81–86) proposed a new explanation for producing Damascus steel using transient nucleate boiling processes. This method involved casting steel into copper molds cooled by cold water, then forging and quenching in specific salt solutions, forming small spherical carbides that created visible chains as a macrostructure.

The replication and experimentation on Damascus steel blades by Obach (2003, pp. 1–29) involved crucible heating followed by heat treatment to create a low-carbon steel rim with a high-carbon steel core. The steel was then hammer-forged and shaped into bar lengths, successfully reproducing dendritic patterns found on wootz crucible steel ingots. The blade's edge durability demonstrated its capability to maintain sharpness and cut through various materials. Metallographic analysis by Williams (2007, pp. 233–241) revealed microstructures containing ferrite with slag inclusions and sorbite near the edge. The carbon content ranged from 0.401 to 0.520%, confirming the presence of carbon in crucible steels and suggesting the possibility of crucible steel, including wootz steel, being traded to Western Europe, potentially by the Vikings.

Smith (1982, pp. 242–244) documented the preparation methods of wootz steel, distinguishing between the Wordsworth and Sehrby method and the Verhoeven method. The Verhoeven process, closer to the ancient method of fabrication, may exhibit property variations due to the impact load during forging, whereas the Wordsworth and Sehrby method, although differing from the original, produces consistent results. Researchers highlighting the importance of adding small amounts of vanadium during production and proposing a model for pattern formation during forging. Micrographs of specific blades illustrated key features necessary for bold surface patterns (Verhoeven et al., 2018, pp. 1331–1336).

Different manufacturing technologies for Damascus steel workpieces have been investigated by Surugiu and Slătineanu (2023, pp. 1355–1361), focusing on forging sheet metal strips with different carbon contents and particle agglomeration techniques. The former method was preferred due to its importance coefficients, which were determined by comparing two-by-two alternatives to solve problems using previously weighted selection criteria. Hynninen et al. (2022, pp. 2484–2491) revealed that blades made in open-air crucibles exhibit surface patterns from a banded cementite/spheroidite microstructure. Metallographic examination revealed higher hardness in the cementite-pearlite blades, indicating that aligned cementite particles formed during the forging process.

Panseri (1965, pp. 5–66) suggested that early smiths used sideritic masses and hot-working methods, such as swaging, to create distinctive patterns on Damascus steel blades. Despite ongoing discussions on Damascus steel classifications, uncertainties remain due to incomplete historical records. Breant (1826, pp. 334–338) presented insights into steel manufacturing processes and alloy formations, proposing a method involving a greasy substance and cochineal to achieve a black or bluish color on steel without diminishing its shine. An experiment blending soft iron and lamp-black indicated potential for crafting high-quality blades.

4 Properties of wootz steel

The physical properties of wootz steel ingots have been investigated by Jaikishian et al. (2021, pp. 15–23), they have examined 45 out of 60 ingots excavated from Konasamudram, Telangana. The results showed uniformity in size, shape, and weight, unlike earlier reported wootz ingots. This led the authors to conclude that a large-scale production unit may have existed in Konasamudram, supplying wootz ingots globally for the production of remarkable swords. The finding is significant as it shifts the interpretation of wootz steel production from isolated artisanal craftsmanship to an organized industrial operation. It implies that ancient Indian metallurgists had achieved a level of process control and standardization comparable to early pre-industrial steelmaking systems. They also suggested that the Damascus steel studied over the past 200 years may have originated in India. Sharada and Srinivasa (2004, pp. 1–146) characterized the microstructure of wootz steel, revealing distinctive Damask patterns with a mix of high-carbon cementite and softer pearlite in a wavy honeycomb structure. Their microstructural mapping confirms that the superior toughness and aesthetic patterns of Damascus steel have metallurgical significance. The alternating cementite–pearlite bands serve both functional and decorative roles, offering early evidence of deliberate microstructure design—a concept central to modern materials engineering. Emission-spectrometer analysis, microscopic examination, and chemical analysis have been used by the researchers to study the effects of impurities on Damascus steel blades, identifying a composition of 1.5 wt% C with high-purity iron and emphasizing the role of trace carbide-forming elements in creating high-quality damascene patterns (Verhoeven et al., 1998, pp. 58–64). This work advances prior descriptive studies by quantitatively identifying vanadium and other trace elements as microalloying agents that stabilize the cementite networks. The correlation between impurity concentration and pattern fidelity provides a mechanistic explanation for earlier visual observations of the Damascus pattern.

Pearson (1795, pp. 322–346) experimented on the properties and composition of wootz steel, noting that it cannot withstand high heat or be welded with iron or steel. The study identified applications such as gun-locks, cutting iron and stones, and making files and saws. Perttula (2004, pp. 92–97) discussed cutting tests, chemical compositions, and impact tests of ancient Damascus steel, showing that blades with uniform carbide distribution were tougher than those with carbide-rich layers. High phosphorus content in Oriental ore often made blades brittle; however, controlled carbon and phosphorus levels in wootz Damascus steel maintained ductility. This analysis introduces a crucial performance-based validation, as it directly links microstructural uniformity to mechanical resilience. Such an approach bridges archaeometallurgy and materials testing, strengthening the argument that ancient Indian steelmakers optimized both form and function. Verhoeven (2007, pp. 559–574) examined the chemical composition, microstructures, raw materials, and forging of wootz steel blades, found that very low amounts of vanadium create the surface patterns. Mushet (1805, pp. 163–175) conducted experiments on five wootz cakes, highlighting a higher carbon content compared to common cast steel and noting issues such as lack of homogeneity and solidity, which were attributed to insufficient heat during manufacturing. Despite imperfections, Mushet concluded that wootz embodies the fundamental qualities of good steel.

The study by Sukhanov (2023, pp. 1481–1493) aims to examine the structural and chemical composition of the primary phases found in 18th-century Damascus saber blades. The results show that chemically, these blades consisted of phosphorus-rich, non-uniform, high-carbon steel. The main

Damascus pattern consists of basins, hollows, crests, hills, waves, and knottiness. The schematic diagram of a genuine Damascus blade and its pattern has been presented in Fig. 2a, b.

The influence of composition on pattern reproducibility has been discussed in the works of Verhoven et al. (1996, pp. 9–22). They propose specific iron mixtures to replicate the carbon levels of traditional Wootz Damascus blades. Metallographic analysis verifies clustered arrays of cementite particles in the ingots' interdendritic regions, essential for forming the characteristic banded pattern in the blades. Verhoeven and Pendray (1993, pp. 175–186) introspected the genuine and reconstructed blades. The results show that cementite particles, responsible for band formation in Damascus steel blades, precipitate from austenite in planar sheets of clustered particles, spaced according to primary dendrite spacing from the ingot. Their results, reinforced by Sukhanov and Plotnikova (2016, pp. 792–802), confirm that the Verhoeven–Pendray mechanism accurately reproduces the morphological and chemical characteristics of authentic Damascus blades. These replications demonstrate that the essential metallurgical principles of Damascus steel are no longer speculative but experimentally verified. They also support the hypothesis of cluster sheet formation as a carbide banding mechanism, wherein impurity elements deform into planar arrays during forging, aiding cementite nucleation along these arrays in the thermomechanical process. However, experiments with blades from vacuum induction-melted (VIM) chill-cast ingots fail to replicate genuine blade patterns and microstructures. The paper discusses ingot segregation, suggesting it may be generated from inadequate crucible mixing. The chemical composition (except iron content) of various wootz steel blades, as described by previous authors, is tabulated in Table 2.

The effect of impurities on the formation of cementite particles in wootz Damascus steel has been investigated by Verhoeven and Jones (1987, pp. 153–180). High levels of phosphorus impurities in Damascus steels significantly impact the formation of cementite particles, which define the distinctive damask pattern of Damascus blades. Experiments on steel castings resembling Damascus steels show that phosphorus prompts primary cementite formation between austenite dendrites during solidification, shaping the final sword's pattern. However, phosphorus impurities also cause cementite to graphitize during certain heat-treat cycles, disrupting the damask pattern. The study highlights the significance of cementite morphology prior to forging and the time–temperature cycle during forging in ensuring the quality of the damask pattern. Further research is

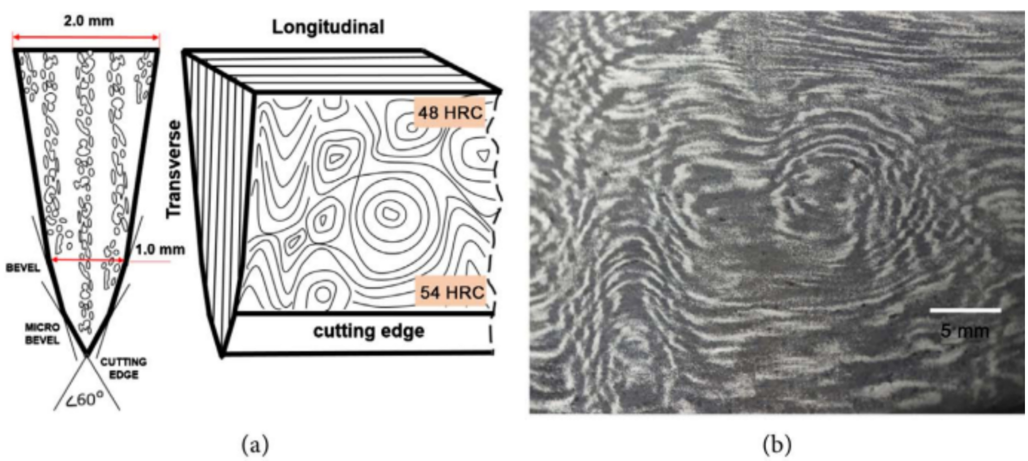

Fig. 2 **a** Schematic of Damascus blade, **b** pattern of Damascus blade [reproduced from Sukhanov and Plotnikova (2019, pp. 118–136) © 2019 by Author(s) and Scientific Research Publishing Inc., open access]

Table 2 Chemical composition of wootz steel

	C	Si	Mn	S	P	V
Verhoeven et al. (1998, pp. 58–64)	1.51	0.05	0.02	0.01	0.11	0.01
Perttula (2001, pp. 65–68)	1.72	0.17	0.21	0.01	0.01	0.00
Williams (2007, pp. 233–241)	1.87	0.049	0.005	0.013	0.127	0.00
Panseri (1965, pp. 5–66)	1.42	0.110	0.130	0.038	0.035	0.00

Weight percentage of reported values in the literature is presented in this table needed to identify the origin of different cementite shapes that contribute to the damask pattern and to understand the role of impurities such as silicon, manganese, phosphorus, and sulfur in cementite particle formation.

Analysis of a replicated wootz blade has been performed by Verhoeven (2002, pp. 356–365). The author reported that the distinctive microstructure of authentic Damascus steel arises from characteristic banding, which requires minimal levels of certain impurity elements, particularly vanadium, in conjunction with a specific thermal cycling treatment. This treatment successfully produced a clustered arrangement of cementite particles in replicated blades, supporting the hypothesis that the bands seen in genuine Damascus blades are a result of this precise combination of conditions. Strobl et al. (2017, 333–340) investigated the metallography of the reproduced Damascus sword. The results showed that the twisted Damascus steel inlays exhibited no defects, while the joints between the inlays and the blade's core revealed scale and oxides in multiple areas. The microstructure ranged from ferrite in decarburized regions to mixtures of martensite, bainite, and ferrite in areas without decarburization. These observed microstructures were correlated with Vicker's microhardness measurements.

Lowe (1989, pp. 237–251) examined the composition, properties, and functionality of an Indian refractory crucible used in the process of melting high-carbon iron and crafting tool-grade steel. The findings highlight the crucible's efficacy in producing high-carbon wootz steel, its contribution to refining ingots into tool-grade steel, and its well-suited thermomechanical properties for the manufacturing process. Wadsworth and Sherby (1997, pp. 1–39) investigated ultrahigh carbon steels (UHCS), detailing their historical development, optimal compositions for superplasticity, and the unique properties that make them suitable for structural applications. This development represents a novel approach, contrary to prevailing steel trends, that employs various thermomechanical processes to achieve diverse microstructures. Engineered ultrafine structures exhibit exceptional room-temperature strength and ductility, while UHCS offers high-temperature formability alongside notable strength and ductility at room temperature. Economical production of UHCS requires low applied force, high strain rates, and temperatures below 800 °C.

The microstructure of a genuine Damascus blade has been explored by Levin et al. (2005, pp. 905–916). The author reported that the distribution of cementite on the sword's surface is uneven, with its presence detected around 6 mm from the cutting edge. Close to the edge, a hexagonal modification of SiO_2 called tridymite is observed, likely due to surface processing. Free graphite is uniformly distributed across the entire surface. Scanning perpendicular to the cementite bands reveals no inhomogeneity. The volume of martensite remains consistent between the surface and cross-section. The weight ratio of ferrite to cementite is 73.3/19.7 and 80.3/15.0, respectively. The steel's texture is more pronounced along the blade's surface, with ferrite, martensite, and cementite exhibiting two directional textures. In the cross-section, no texture is found for cementite. Ferrite grains appear needle-like, while other phases have a plate-like structure. High-resolution transmission electron microscopy (HRTEM) analysis confirms the presence of nanowires and surrounding phases. Sukhanov et al. (2016, pp. 59–65) introspected the structure of Damascus steel preforging, highlighting the pearlite matrix and the absence of secondary free cementite. The transformation of ferrite and ledeburite during thermomechanical treatment is explored, including the recrystallization of ledeburite into a more stable phase during forging. The study establishes limits for the transformation of high-carbon alloys into Damascus steel and analyzes the influence of modifying additions such as aluminum and calcium on ledeburite formation and alloy ductility. Torsion tests on alloyed specimens with varying eutectic morphologies validate ductility peaks in the inter-critical temperature range. Varying the degree of melt supercooling results in steel with carbon content resembling white cast iron. The properties of wootz steel along with its microstructure have been investigated by Sukhanov and Plotnikova (2016, pp. 792–802). They reported that wootz steel displays a distinctive excess carbide phase not found in other iron-carbon alloys, consisting of angular eutectic carbides with irregular trigonal-prismatic shapes. Its microstructure features a ferritic matrix with secondary cementite uniformly dispersed, usually in round or oval shapes without clear angles. The formation mechanism of these angular carbides in pure iron-carbon alloys remains unclear, but it is believed to result from the deformation process and the accumulation of defects, such as dislocations, around carbide clusters. Collectively, these studies broaden the understanding of microstructural evolution in wootz steel. The identification of troostite–carbide interfaces and angular eutectic carbides suggests that ancient smiths achieved exceptional control over phase transformations. These findings bridge classical forging practice with contemporary thermomechanical theory.

Evaluation of wootz steel microstructures using optical microscopy, SEM, and Electron Backscatter Diffraction (EBSD) has been presented by Kumar et al. (2012, pp. 802–805). The observations indicate that bulky carbides are dispersed within a pearlitic matrix, alongside different forms of cementite distributed across various deformation regions. Increased deformation led to the breakdown of the cast structure, suggesting a mechanism for the spheroidization of cementite in hypereutectoid steel. Regions of high strain exhibited fine equiaxed ferrite grains surrounded by high-angle boundaries. The thermomechanical working refines the steel's structure, transforming brittle cast hypereutectoid steel into a durable and robust material composed of spheroidized cementite in a ferrite matrix.

Paetzke et al. (2010, pp. 47–65) investigated the nanoindentation behavior in conjunction with the microstructure of wootz steel parts. Nanoindentation experiments revealed that the nanohardness and elastic modulus of wootz steel were influenced by its microstructure and phase content. Cementite particles arranged in bands were found to contribute to the distinctive damask pattern observed in wootz steel. Furthermore, the presence of cementite nanowires and carbon nanotubes was detected. Transmission electron microscopy (TEM) was utilized to analyze the structure at the nanometer scale, with specific findings discussed independently.

The interconnections among superplasticity, Damascus steels, laminated steels, and carbon dating have been presented by Wadsworth (2016, pp. 3150–3160). The author explores the archaeometallurgy of swords, with a focus on knives that have mysterious processing backgrounds. Experiments on laminated materials demonstrate that microstructural layering is lost at a scale of approximately 1 μm. Mechanical properties, such as Charpy V-notch toughness, can exceed those of individual steels in UHCS-mild steel laminated composites. Interestingly, strengthening interfaces through heat treatment can result in property degradation in laminated composites. In other works, Sherby and Wadsworth (1997, pp. 32–39) highlight that UHCS with ultrafine ferrite grains and fine spheroidized cementite particles exhibit an impressive combination of strength and ductility at room temperature. The UHCS material demonstrates a yield strength of 920 MPa, an ultimate strength of 1145 MPa, and a total elongation of 12%. A significant strength enhancement of UHCS sheet compared to conventional and advanced automotive steel sheets is noted when assessed at equivalent tensile ductility levels. These findings provide support for the historical claims regarding the workability of ancient Damascus steels and underscore the substantial potential of UHCS for structural applications.

Discussions about ancient steel and laminated composites have been presented by Wadsworth (2002, pp. 980–987). The author employs modern accelerator mass spectrometer methods to directly date steels, utilizing very small material samples. Research discusses the production of UHCS for studying superplasticity and fabricating laminates to examine composite material behavior. Additionally, it references specialized straight-edged krisses made from low-carbon steels and meteoric iron. Achieving superplasticity in steels requires a higher carbon content, as seen in UHCSs, which resembles the compositions of Damascus steels. The study investigates the behavior of laminated composites composed of UHCS and mild steel, highlighting toughness variations with temperature.

The study by Rehren and Papakhristu (2000, pp. 55–69) examines crucible steel smelting in the Ferghana Valley, with a focus on crucible sizes and shapes. It estimates steel ingot volume with about 10% accuracy. Mass balance calculations consider ingot and slag compositions, along with crucible volumes, to determine the iron content and the amount of charcoal needed. Experimental trials in Kurgan successfully produced steel ingots with slag. The study highlights limitations in data and urges further analysis on slag composition, non-metallic inclusions, fluxing components, and ceramic erosion. It emphasizes the need for more research to fully grasp the process's chemistry and dynamics.

Židzik et al. (2021, pp. 1616–1620) evaluated the mechanical properties of Damascus steel, particularly its hardness and toughness. Hardness measurements of Damascus steel samples revealed values between 53 to 56 HRC, averaging around 55 HRC, which corresponds to approximately 86% of the hardness of the hard phase. Additionally, the energy required to fracture a Damascus steel sample was determined to be 10.72 J, accounting for 18% of the value observed for the tough component. Examination of fracture surfaces offered insights into the internal structure and patterns of Damascus steel.

Failure analysis along with the impact strength of welded Damascus steel has been experimentally investigated by Mintách et al. (2012, pp. 22–28). Damascus steel, composed of STN 41 4260 spring steel and STN 41 9312 tool steel forged into layers of 84 or 168, underwent impact strength testing across a range of temperatures (−60 to 160 °C) after heat treatment. Results indicated ductile fractures at higher temperatures and increased cleavage facets at lower temperatures, with STN 41 9312 steel exhibiting consistent impact strength. Microscopic analysis revealed that microcracks tended to initiate and spread within the welding layers of Damascus steel. The study explored the impact strength and notch toughness of experimental steels, particularly Damascus steels, at varying temperatures. It observed a decrease in impact strength with decreasing temperature, accompanied by a shift towards more cleavage facets. Notably, STN 41 9312 steel maintained consistent impact strength across temperatures. Charpy U-notch impact testing indicated a decline in notch toughness with decreasing temperature for both Damascus steels, with the steel featuring more layers showing higher toughness. The microstructure of Damascus steel, characterized by alternating layers of different steels, revealed welding layers as sites prone to the initiation and propagation of multiple microcracks.

Verhoeven et al. (1990, pp. 205–227) experimented with different forging temperatures and levels of metal flow to craft blades from a Fe–1.6 wt% C alloy, aiming to analyze Damascus microstructure. Methods included metallography to analyze the microstructure, infrared pyrometry to monitor workpiece temperature during forging, and examination of the spheroidization characteristics of particles in heated samples. Various forging techniques were employed to evaluate the efficacy of internal stress. While the Wadsworth-Sherby technique exhibited macroscopic similarities to Damascus blades, microscopic analysis revealed distinct differences, particularly in the morphology of cementite particles and void formation. Heating unforged steel with a grain boundary allotriomorph structure resulted in the dissolution of cementite without void formation. Extended high-temperature heating of forged bars led to cementite disappearance and void formation, which were less prominent at lower temperatures.

The chemistry, microstructure, and properties of Damascus swords have been reported in the works of Peterson et al. (1990, pp. 355–374). The study examined the microstructure, chemical composition, and mechanical characteristics of Damascus steel swords. It identified a hypereutectoid steel microstructure featuring a pearlitic matrix with spheroidized primary cementite arranged in aligned layers. The steel exhibits low impurity levels and is relatively pure. Mechanical testing reveals properties similar to those of carbon steels, but with enhanced yield and tensile strength attributed to finer pearlite spacing, resulting in increased elongation and reduced area reduction. The presence of a ferrite-rich spine along the blade's center suggests a decarburized surface was retained during forging, shedding light on the duration of the forging process. Heat treatment yields a refined pearlitic matrix, aligning with expectations for high-performance carbon steel.

The metallurgy of Damascus steel and ultra-high carbon steels was compared in the works of Wadsworth and Sherby (1980, pp. 35–68). Discussions about the metallurgical aspects of Damascus steel production, including the distinct markings found on these blades, were presented. The authors propose a manufacturing method based on experimental findings and a review of historical literature. They suggest that their approach aligns with observed microstructures in Damascus blades and historical practices, particularly regarding color as a guide to temperature during forging and heat treatment.

The key characteristics that identify authentic Damascus blades have been outlined by Verhoeven and Peterson (1992, pp. 335–341), and they presented data on a newly analyzed genuine blade. By following the described procedure, a microstructure resembling genuine Damascus steel can be achieved, typically with an average "n" value ranging from 4 to 6. Genuine Damascus blades exhibit a planar arrangement of parallel sheets in their microstructure, with evenly distributed particles throughout both longitudinal and transverse sections. The matrix comprises fine pearlite, with nearly equiaxed particles averaging around 5 μm in diameter. The spacing between cluster cementite sheets on transverse sections is approximately 50 μm.

The unique nature of excess cementite in Damascus steel has been discussed by Sukhanov et al. (2017a, pp. 40–46). Damascus steel takes the form of irregular prisms known as angular eutectic carbides, unlike other cementite phases in iron-carbon alloys. The authors propose three hypotheses for the formation of this excess cementite: thermal fission, fragmentation during deformation, and transformation from metastable to stable angular eutectic carbide. Through experiments demonstrating the conversion of high-purity white cast iron into Damascus steel via isothermal soaking at annealing, the study suggests that Damascus steel belongs to the non-heat-resistant ledeburite class of steel. While sharing structural characteristics with semi-heat-resistant die steel or heat-resistant high-speed steel, Damascus steel differs in the nature of its excess carbide phase. In Damascus steel, carbide heterogeneity exclusively comprises angular eutectic carbides, with the metastable ledeburite showing reduced micropores and lacking pronounced layering compared to lamellar and cell ledeburite in white cast iron. The microstructure of wootz steel is shown in Fig. 3. Higher magnification micrograph of Damascus steel blade shows fiducial mark as labelled on the micrograph and the concentric rings of alternating bands of cementite/spheroidite to its left.

In another study, Sukhanov (2020, pp. 26–37) discusses the influence of phosphorus on the structure of Damascus steel. The results indicate that genuine Damascus steel is characterized by its high purity and non-alloy, high-carbon composition with elevated phosphorus content, which aids in carbon segregation during crystallization. Crack branching along carbide and troostite layers reduces crack growth energy in this steel. Impurities, particularly phosphorus, lead to decreased mechanical properties. The study by Sukhanov et al. (2016, pp. 59–65) examines the morphology of excess

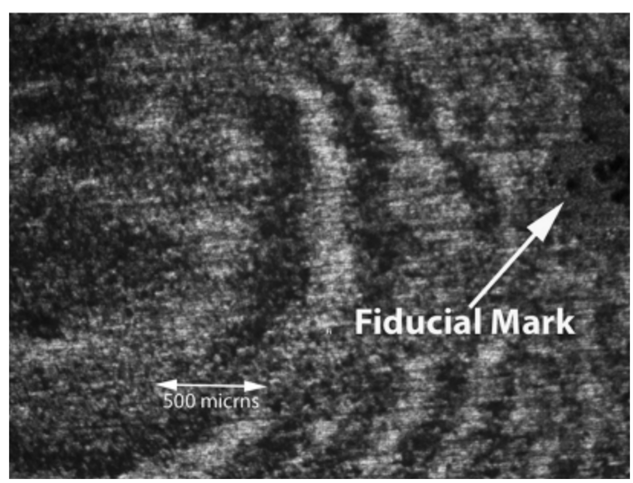

Fig. 3 Micrograph of a Damascus steel blade (reproduced with permission from Hynninen et al. (2022, pp. 2484–2491) © 2022, The Minerals, Metals & Materials Society)

carbides in Damascus steel, investigating their formation and characteristics across various alloys and conditions. It highlights that certain types of wootz, similar to white cast irons in carbon content, lack a ledeburite structure but are composed entirely of eutectic carbides with a prismatic shape. X-ray phase analysis of alloy BU22A identifies ferrite and cementite as the major phases; however, precisely identifying the excess carbide phase is challenging due to the overlapping lines of secondary cementite. In BU22A, excess carbides exhibit a faceted prismatic shape, which is formed during forging deformation, thereby enhancing their thermal stability compared to Widmanstätten cementite. The authors also present a hypothesis regarding the thermal process involving the division of plates of secondary cementite or ledeburite into isolated single grains and the formation of spikes on cementite surfaces during annealing.

The detection of unusual excess cementite in Damascus steel specimens was conducted by Sukhanov et al. (2017b, pp. 1–7). The study reveals that certain Damascus steel samples contain excess cementite, known as angular carbides, with irregular octahedral and prismatic shapes formed within metastable ledeburite colonies. It also discusses how unalloyed materials of the carbide class acquire Damascus steel properties through annealing, which separates metastable ledeburite colonies thermally, restricts newly formed eutectic carbides, and allows subsequent coalescence. Additionally, it addresses the unusual coarseness of excess carbides in Damascus steel, which resembles that found in ledeburite steels, suggesting that limited carbon saturation of primary austenite crystals during melt solidification leads to the formation of high-carbon steel instead of the ledeburite eutectic in Damascus steel.

Sukhanov (2022, pp. 453–468) in another work also mentioned that genuine Damascus steel displays a distinct structure featuring troostite-carbide banding, with troostite layers measuring 450 HV in microhardness and carbide layers reaching 950 HV. The main patterns include hollows, hills, saddles, crosses, and wavy dunes, forming a disordered arrangement across the surface. Destruction involves intragrain cleavage, micropore fusion, and inter-grain cracking, leaving mixed relief details on fracture surfaces. The dispersion of troostite and carbide layers follows the golden section rule, crucial for crack directionality during impact. While the damask pattern doesn't notably affect mechanical properties, it indicates the quality of the banding structures. The eutectoid matrix comprises pure quenching troostite, with lamellar troostite making up about 80%. Damask structures consist of horizontal sinuous lines resembling slopes or steps, mathematically describable for macrostructure control.

Srinivasan (2007, pp. 279–280) describes that the Indian method of making wootz steel cake unveiled the presence of carbon nanostructures, including cementite nanowires enclosed by carbon nanotubes (CNTs). Another carbon allotrope, buckminsterfullerene (C60), was discovered during the laser ablation of graphite in helium. The repeated heating and forging of wootz steel led to the formation of bands due to impurity segregation at a microscopic level. Damascus blades, made from wootz steel, exhibit high mechanical strength and flexibility, possibly attributed to carbon nanostructures, such as CNTs. Henry (1852, pp. 212–213) studied the composition of wootz steel, and the results showed that samples obtained from India have a composition of wootz steel with varying levels of carbon, along with traces of other elements such as silicon, sulfur, and arsenic.

Thiele et al. (2015, pp. 720–739) indicated that pattern-welding in medieval swords was mainly ornamental and didn't notably improve their performance. Mechanical tests showed no benefit from pattern-welding. Material preferences in sword making were assessed using multi-criteria analysis. Metallographic and carbon content analyses were performed to delve into the composition and structure of sword samples. These results underscore the importance of considering both decorative and functional elements in the study of historical sword craftsmanship.

5 Current research

Gazzi et al. (2016, pp. 273–278) presented a modern metallurgical technique using neutron diffraction to determine the fabrication and properties of Indian swords. Neutron diffraction identified the microstructural and compositional characteristics of the swords, revealing that one blade might have been forged from wootz steel. This finding underscores the potential of neutron analysis for identifying wootz steel blades without damaging them. Another blade showed signs of pattern welding with arsenic to mimic wootz steel's characteristics, while a third blade had evidence of added austenitic steel, likely due to repairs. This combination of neutron-based methods provides valuable insights into the composition and history of these historical blades.

A wootz steel blade has been investigated in the works of Sullivan et al. (2007, pp. 1104 CD–1105 CD) using electron backscatter diffraction (EBSD) to understand the microstructure. The results revealed three types of cementite particles in a ferrite matrix: large block-shaped particles, thin particles along the edges of previous austenite grains, and small, evenly distributed particles. The study also explored the orientation of the cementite particles within the wootz matrix by examining their crystal structures and textures at various points in the blade, reporting a strong "010 fiber" in the cementite.

The EBSD characterization of an ancient wootz steel blade from ancient India has been performed by Barnett et al. (2009b, pp. 252–260). The study concluded that the prior austenite grain size was approximately 20–30 µm, with no distinct elongation in the longitudinal direction. The carbide banding was not extensive, and the morphology of the pro-eutectoid cementite was unremarkable. Verhoeven et al. (1993, pp. 187–200) discussed the destruction and reformation of the damask pattern, revealing that the formation of clustered cementite particle sheets in genuine blades results from carbide banding during cyclic forging, with third elements influencing nucleation.

Sukhanov and Plotnikova (2019, pp. 118–136) studied the influence and distribution of carbide on the properties of genuine Damascus steel. Using various analytical techniques, they investigated the chemical composition and structure, revealing that genuine Damascus steel is distinguished by its high purity, which is achieved through the use of unalloyed high-carbon steel with increased phosphorus levels. This results in a varied distribution of excess carbides within the troostite matrix. Hardness tests indicated that carbide layers in genuine Damascus steel were around 920 HV, while the troostite matrix measured approximately 475 HV. Sullivan and Barnett (2009, pp. 1496–1497) performed EBSD analysis on a reconstructed wootz steel blade to investigate the connection between thermomechanical processing and carbide microstructures. The analysis revealed banding and orientation clustering similar to those of the genuine wootz blade, indicating successful fabrication.

The influence of phosphorus-rich bands on the microstructure of hypereutectoid wootz steel and finding correlations with internal cracking, carbon depletion, along with increased spheroidized cementite frequency over pearlite has been discussed in the works of Barnett et al. (2009a, pp. 2192–2197). Park et al. (2022, pp. 408–421) published a study on modern neutron diffraction analysis along with metallographic characterizations of wootz steel samples. Their objective was to detect anisotropy in grain orientations through diffraction patterns. Metallographic analysis revealed a sophisticated method for managing carbide precipitation in high-carbon steel, while neutron diffraction demonstrated the anisotropic orientation of cementite grains. This technique of controlled microstructure formation was pioneered in India. Salvemini et al. (2020, pp. 1–10) utilized neutron imaging methods to identify the microstructures of ancient Indian blades. Both polychromatic and monochromatic methods were employed to study structural properties and manufacturing techniques, especially surface pattern formation. Radiographs and tomographic reconstructions revealed that surface patterns were etched, indicating consistent material composition across the blades.

Gargade (2019, pp. 37–55) discussed the existence of nanotechnology in ancient India in wootz steel. Indian craftsmen employed unique smelting methods to craft Damascus blades, resulting in a microstructure generated at the nanoscale, where carbon atoms were arranged cylindrically. Wootz steel, the material used for making Damascus swords, contains iron carbide particles (Fe_3C), also known as cementite, which typically contributes to its brittleness. Reibold et al. (2009b, pp. 305–310) reported the discovery of nanotubes in ancient Damascus steel. The study employed high-resolution electron microscopy to analyze 17th-century Damascus sabers, revealing cementite nanowires and carbon nanotubes that were only visible after dissolving the sample in hydrochloric acid. In another study, Reibold et al. (2009a, pp. 1139–1146) further explored the nanoscale structural analysis of several historic blades, indicating that ancient and modern Damascene steel blades share a nanostructure composed of colonies of wire- and tube-like particles.

Reibold et al. (2006b, p. 286) observed the presence of carbon nanotubes within an authentic Damascus sabre using high-resolution transmission electron microscopy. These nanotubes comprised multi-walled tubes with a layer distance of 0.34 nm. Anand et al. (2024, pp. 1–4) studied the microarchitecture and nanoscale hierarchical structures of carbon in ancient archaeological carburization slags. The results showed that carbon structures found in ancient carburization slags, spanning from 400 BCE to the sixteenth century CE, reveal a hierarchical organization consisting of carbon micro-rods at the micro-scale, composed of finer carbon micro-rods arranged coaxially. Sanderson (2006, p. 1) analyzed Damascus sabres to understand the presence of nanotubes in the steel, unveiling nanotubes within the steel through a method involving the dissolution of cementite nanowires using hydrochloric acid.

Deshmukh (2019, pp. 3–14) examined the advancement of ancient technology in terms of nanotechnology, specifically in wootz blades, highlighting the ancient art of crafting wootz steel, as seen in Damascus blades, which foreshadowed modern nanotechnology by manipulating materials at the atomic level. Kochmann (2004, pp. 15–19) reported the investigation of nanowires in Damascus steel, revealing that authentic Damascus sabers possess a dense array of cementite nanowires. Papadatu et al. (2023b, pp. 1367–1380) presented a detailed analysis of genuine Damascus steel, focusing on selecting high-quality materials to create authentic Damascus steel and conducting additional studies to comprehend and assess the behavior of Damascus steel under various scenarios and loads. Reibold et al. (2006a pp. 1172–1182) analyzed the microstructure of annealed samples from an authentic Damascus saber using X-ray phase analysis and high-resolution electron microscopy.

Kürnsteiner et al. (2020, pp. 515–519) utilized laser additive manufacturing to create intricate three-dimensional metallic parts from computer-aided design models, employing a novel Fe19Ni5Ti alloy tailored for laser additive manufacturing to control martensite transformation and precipitation during fabrication. Pacchioni (2020, p. 481) aimed to develop Fe19Ni5Ti using laser additive manufacturing to create complex metal objects, focusing on the pause time between layers to control local microstructure. Stelzner et al. (2016, pp. 86–101) performed X-ray CT analysis of early Medieval swords to reveal construction and manufacturing processes, examining 30 swords to reveal detailed information about blade construction, including the presence of twisted and non-twisted composite rods.

Boatner et al. (2017, pp. 666–671) discussed traditional Damascus steel processes and introduced an innovative method involving the cryogenic quenching of polished austenitic alloy single crystals into the martensitic phase to generate unique surface patterns, thereby bypassing the need for forging altogether. Potential applications span knives, art pieces, furniture, and jewelry.

6 Summary and future scope

The rich history and impressive qualities of Damascus steel have made it a subject of intense academic interest and comprehensive study. Its unique microstructure, characterized by the ferrite-cementite phases, the presence of phosphorus, and deoxidation products, demonstrates superior longevity and cutting ability compared to contemporary carbon tool steel. Numerous sophisticated analysis techniques have been instrumental in decoding the complex microstructure of Damascus steel. X-ray phase analysis, Electron Backscatter Diffraction (EBSD) analysis, and electron probe microanalysis have played significant roles in understanding the intricate relationship between the microstructure of this steel and its superior mechanical properties.

One of the significant breakthroughs in this field has been the discovery of carbon nanotubes and cementite nanowires in Damascus steel, revealed through high-resolution electron microscopy. The presence of these nanostructures suggests an intriguing link between ancient metallurgy and modern nanotechnology. The formation of these nanostructures is believed to be a consequence of the steel's thermomechanical processing and is likely to play a crucial role in enhancing the steel's strength and its characteristic banding pattern. Despite the remarkable analytical progress achieved so far, the present understanding of wootz steel remains incomplete to a certain extent due to the unavailability of original, well-preserved crucible and ingot samples. This limitation calls for a shift toward replicative, computational, and non-destructive research approaches. Computational thermodynamics can simulate the carburization and solidification conditions of ancient crucibles, providing valuable insights into phase evolution, impurity control, and carbide formation. Similarly, neutron diffraction and electron backscatter diffraction (EBSD) techniques can be employed on surviving artifacts to extract microstructural information without damaging them. Such interdisciplinary integration can reconstruct the lost manufacturing processes with scientific precision. Efforts to replicate the properties of Damascus steel have led to the development of advanced manufacturing techniques such as spray forging and laser additive manufacturing. These techniques, combined with metallurgical phase transitions, have shown considerable promise. The materials created using these techniques have demonstrated a tensile strength of 1300 MPa and an elongation capacity of 10%, mirroring the traits of ancient Damascus steel. Several key experimental findings are particularly noteworthy from a metallurgical perspective. It has been demonstrated by previous researchers that trace vanadium and controlled thermal cycling were central to forming the distinctive damask patterns. The ancient forging cycles have been reproduced, leading to verification of comparable microstructural and mechanical performance between reconstructed and authentic blades. The recent study indicates the presence of cementite nanowires and carbon nanotubes, providing evidence that ancient smiths, unknowingly, achieved nanoscale structural refinement through repeated forging. These studies demonstrate that the mechanistic basis of wootz steel production is now understood in metallurgical terms, even though the original crucible artifacts are no longer available for direct testing.

Despite major progress in replicating the properties of Damascus steel, several historical and experimental studies have not revealed its original production methodology, which requires further research in the future. The observations of Indian smiths in the eighteenth and nineteenth centuries (Verhoeven, 1987, pp. 145–151; Barnett et al., 2009b, pp. 252–260) made by Britishers documented the crucible-based carburization of wrought iron, slow cooling, and controlled forging cycles, procedures consistent with modern reconstructions. The claim of a decisive role played by the presence of trace vanadium in the native ore that lays an aligned cementite bands is to be re-examined. Although this mechanism, as revealed through microstructural and mechanical comparisons of reconstructed and ancient blades, is to be reinvestigated, and how it can be achieved with simple and elegant techniques used by ancient Indian metallurgists, is to be rediscovered. These findings collectively indicate that the core metallurgical principles behind the production of wootz steel are yet to be well understood, and certain practical aspects of large-scale processing and regional variations remain topics of active research. The once-mysterious “secret” of Damascus steel is now substantially elucidated through metallurgical analysis. However, the craftsmen and the precise control of the material's microstructure at the atomic level must be pursued as a part of ongoing investigation. The patterned microstructure may have formed from the alignment of cementite sheets that developed during cyclic forging, a phenomenon intrinsic to the steel's chemistry that needs further investigation. Thus, while subtle regional techniques and crucible compositions still invite further study, the essential mechanisms responsible for the famed Damascus pattern have yet to be decoded to full extent. Therefore, the preservation and in-depth study of original Damascus steel artifacts assume paramount importance. These artifacts provide invaluable insights that can significantly enhance our understanding of this remarkable material and its production techniques. Moreover, they stand as a testament to the incredible skills and knowledge of the ancient craftsmen who first created Damascus steel. This feat continues to inspire and challenge the modern world of materials science, motivating us to reach new heights in technological advancement. The opportunity to learn from these ancient artifacts anchors us to our past and guides our steps into the future, ensuring that the legacy of Damascus steel continues to influence generations of scientists and craftsmen. Looking ahead, the future scope of this research lies in combining archaeometallurgy with modern materials science. Additive manufacturing can be leveraged to engineer functionally graded steels with microstructural banding analogous to wootz, while computational phase modeling can predict optimal compositions and heat-treatment paths. Establishing a digital archive of reported wootz compositions, micrographs, and mechanical data would also enable cross-regional comparison and machine-learning-based prediction of damask pattern formation. In essence, the lost art of wootz production can evolve into a living experimental framework that informs the design of next-generation high-carbon and nano-engineered steels.

The legacy of Damascus steel, characterized by its unique microstructure and superior mechanical properties, has been a subject of fascination and study, providing insights into the sophisticated metallurgical practices of the past. Despite advancements in our understanding, the exact methodologies of the original production of Damascus steel remain elusive, enhancing its allure as an emblem of technological prowess and innovation. The application of advanced analytical techniques has enriched our contemporary understanding of Damascus steel's properties. Notably, high-resolution electron microscopy has revealed the presence of carbon nanotubes and cementite nanowires, bridging a fascinating connection between ancient metallurgy and modern nanotechnology. This discovery underscores the sophistication of ancient metallurgical practices and opens new avenues for exploring the potential applications of these nanostructures in contemporary materials science.

Efforts to replicate the unique properties of Damascus steel have led to the development of innovative manufacturing techniques, such as spray forging and laser additive manufacturing, which have shown promise in creating materials with comparable mechanical properties to those of Damascus steel. This successful application of modern techniques underlines the enduring relevance of the ancient knowledge encapsulated in Damascus steel. Thus, the ongoing study of Damascus steel is not merely an exploration of an ancient material but a tribute to the human spirit of curiosity and invention. Damascus steel's legacy extends beyond its historical context, serving as an enduring symbol of human ingenuity. As we continue to decode its secrets and learn from its wisdom, it remains a beacon of inspiration, guiding our journey into the future of materials science.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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