

Iron in Islam and the Evolution of Metallurgy: Integrating Revelation, Science, and Technology Toward a Sustainable Future

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1. Introduction

Throughout the history of human civilization, iron has played a vital and strategic role. Its presence marked a milestone in technological development from the prehistoric era to the historic era through a phase known as the Iron Age, during which societies of that time began to move away from the use of stone and bronze to utilize iron in their daily lives (Ashby et al., 2007). From agricultural tools and weapons to early infrastructure, iron became a symbol of technological transition and the dominant power of a civilization. The use of iron continues to this day as the most widely used metal in the world (Pilchin & Eppelbaum, 2006). In the era of Industry 4.0 and as we enter the Society 5.0 phase, iron remains a mainstay in construction, industry, machinery, the automotive sector, tools, and other fields—whether in the form of minerals, elements, metals, compounds, or alloys.

In the context of the formation of the universe, iron atoms accumulate at the core of high-mass stars, triggering supernova explosions, which led to the formation of the solar system, Earth, and ultimately life. Molten iron in the Earth's core generates the Earth's magnetic field and creates the Van Allen radiation belts, which protect life on the Earth's surface from damaging, high-energy, penetrating cosmic radiation and safeguard the vital ozone layer (Denton, 2020). The radiation belts, also known as the magnetosphere, are illustrated in Figure 1 below (Yahya, 2005).

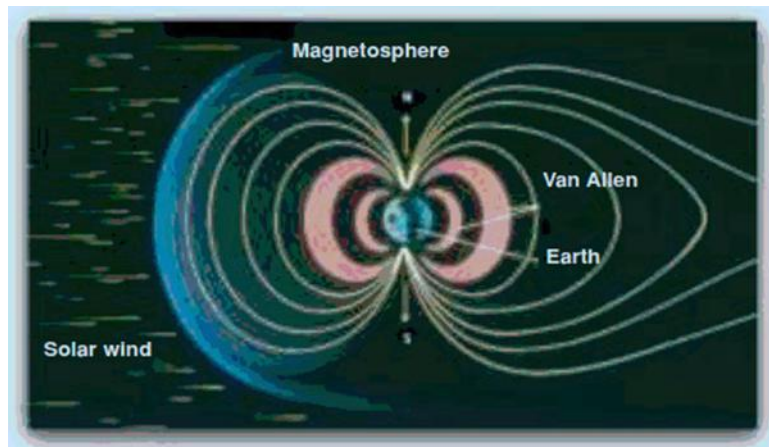


Figure 1: The Van Allen Belts

Iron carries oxygen in the blood as the main component of hemoglobin in red blood cells. Iron also plays a key role in the formation of several enzymes in the human body. Iron is also used as a treatment for people with anemia. Iron oxide particles are utilized in cancer treatment — magnetic fluid hyperthermia (high-temperature magnetic fluid)—by a team led by Dr. Andreas Jordan at the world-renowned Charité Hospital in Germany, which successfully killed cancer cells using a new method (Gheraout, 2017). In the human body, iron functions to transport oxygen from the lungs to tissues and to transport electrons in the process of energy production

within cells. An adult male (weighing 75 kg) contains approximately 4,000 mg of iron, while an adult female (weighing 55 kg) contains approximately 2,100 mg of iron (Umar et al., 2020).

Iron, as an element, consists of iron atoms. Iron plays a crucial role in the creation of the universe, life on Earth, and human civilization. Without iron atoms, there would be no carbon-based life in the cosmos; no supernovae, no heating of the primordial Earth, no atmosphere, and no hydrosphere. There would be no protective magnetic field, no Van Allen radiation belts, no ozone layer, no metal to form hemoglobin (in human blood), no metal to tame the reactivity of oxygen, and no oxidative metabolism. The fascinating and intimate connection between life and iron—between the red color of blood and the death of distant stars—not only highlights the metal's relevance to biology but also the biosentrisitas of the cosmos (Gheraout, 2017).

Iron is a non-technical and non-economic element in technological and industrial applications. The well-known engineering forms of iron are cast iron and steel. Cast iron, with its various specifications, and especially steel, with its diverse functional properties in many products, have not yet been fully replaced by other materials. Iron and its derivatives remain the backbone of modern technological development, ranging from structural steel and special alloys for aerospace to iron nanoparticles in the medical field and renewable energy.

2. Iron from the Perspective of the Qur'an

Iron is the only metal that holds a special place in the Qur'an. "Iron" is the name of the 57th surah in the Qur'an. The revelation of verse 25 of Surah Al-Hadid began during the Battle of Uhud, which took place during the early days of Islam in the city of Medina (Kustomo et al., 2022). Iron is explicitly mentioned with special emphasis on its benefits and strength for humanity, as stated in Surah Al-Hadid, verse 25, which reads in full:

لَقَدْ أَرْسَلْنَا رُسُلَنَا بِالْبَيِّنَاتِ وَأَنْزَلْنَا مَعَهُمُ الْكِتَابَ وَالْمِيزَانَ لِيَقُومَ بِالْقِسْطِ وَأَنْزَلْنَا الْحَدِيدَ فِيهِ بَأْسٌ شَدِيدٌ وَمَنَافِعُ لِلنَّاسِ وَلِيَعْلَمَ اللَّهُ مَنْ يَنْصُرُهُ وَرُسُلَهُ بِالْغَيْبِ إِنَّ اللَّهَ قَوِيٌّ عَزِيزٌ

"Indeed, We have sent Our messengers with clear proofs, and We revealed with them the Scripture and the scales (of justice) so that people may act justly. And We revealed iron, which possesses great strength and many benefits for humanity, and so that Allah may know those who support His religion and His messengers, even though they cannot see Him. Indeed, Allah is the All-Mighty, the All-Powerful." (Quran 57:25).

This verse assigns iron a special position: placed directly alongside revelation (the Book) and justice (the scales), as an instrument of civilization. The use of the word "*anzalnā*" (We sent down) in the phrase "*wa anzalnā al-ḥadīd*" has been a key point of discussion in both classical and contemporary exegesis. "Sent down" can be interpreted literally to mean that iron was sent down directly by Allah or that only Allah created iron (Nasr et al., 2015), just as revelation or rain is sent down.

Iron is not a naturally occurring element on Earth. Iron is not formed on Earth but rather falls to Earth from outer space (Dadach, 2015). This phenomenon aligns with the scientific view that iron entered Earth's atmosphere from outer space via meteorites (containing 10% iron) approximately 4.6 billion years ago (as old as the solar system itself), which reinforces the literal meaning of the "descent" of iron (Herbst & Greenwood, 2019). According to a study by Professor Armstrong and Mohamed Asadi, a scientist at NASA, iron is a unique metal whose formation requires an enormous amount of energy—exceeding the energy produced by the solar system (Novie et al., 2024).

In addition to Surah Al-Hadid, verse 25, which provides information about the origin of iron, there are five other surahs and six additional verses in the Qur'an that discuss iron. These surahs are: Al-Isra (17), verse 50; Al-Kahf (18), verse 96; Al-Anbiya (21), verse 80; Al-Hajj (22), verse 21; Saba (34), verse 10; and Saba (34), verse 11. The mention of iron in several surahs and verses of the Qur'an serves as confirmation that Allah has bestowed iron as a blessing, with its value and benefits for humanity. However, it is important to remember and understand that the Qur'an is not a *science* textbook; rather, as the holy book for Muslims, it contains guidelines for life and verses that provide inspiration, guidance, and knowledge about the universe and life. Several verses in the Qur'an touch on scientific aspects that have been proven to align with scientific discoveries, including the recognition of iron as an essential material in human life (Anggara et al., 2023).

3. Iron from the Perspective of the Hadith

Unlike the Qur'an, which mentions iron explicitly and philosophically, references to iron in the hadith tend to be more practical and contextual, relating to its function and use in daily life. Although there are not many hadith that specifically discuss iron as a main theme, it appears in various narrations, particularly those related to warfare, social life, and as a symbol of strength. In Sahih al-Bukhari, there are 91 hadiths that mention the word "*hadid*" (Aprilia Dewi Ardiyanti, 2022). However, in Sahih al-Bukhari and Sahih Muslim, there are 17 hadiths that mention the word "iron" in their translations (Baqi, 2017).

Among the hadiths regarding iron are the following. Abdullah bin Yusuf narrated to us, and Malik reported to us from Yahya bin Sa'id, who said, "I heard Abu al-Hubab Sa'id bin Yasar say, 'I heard Abu Hurairah, may Allah be pleased with him, say: 'I was commanded (to migrate) to a place whose appeal is greater than that of other places, namely the city of Medina; this city purifies people (of evil) just as a blacksmith's anvil purifies iron of its rust.' (Narrated by al-Bukhari, No. 1738) (Salmah, 2016).

Another well-known hadith narrated by Imam Bukhari and Muslim states: "Whoever carries a (iron) weapon to intimidate his fellow Muslim, the angels will curse him, even if he is his own blood brother." (Narrated by Muslim, No. 2616). There is a narration in this hadith specifying that the weapon in question is made of iron. This indicates that iron (as a weapon) possesses extraordinary power, but its misuse contradicts the principles of compassion and social security in Islam. This demonstrates that metals such as iron are not morally neutral, and their use depends heavily on human intent and purpose. Therefore, ethical control over their use is of utmost importance from an Islamic perspective.

In the context of warfare and self-defense, another authentic hadith mentions the Prophet's military equipment, such as: "The Messenger of Allah entered Mecca on the day of the conquest wearing an iron helmet (*mighfar min hadid*)."

 (Narrated by Bukhari, no. 5361). This indicates that the Messenger of Allah did not reject the use of technology (in this case, weapons or protective gear made of iron) for strategic purposes and to ensure safety. That iron helmet was a form of military technology at the time, and it demonstrates that the use of strong materials like iron is part of a rational and contextual Sunnah. Several hadiths also mention iron in the context of an iron chair (Narrated by Muslim, No. 1450); military equipment, namely armor and spears (Narrated by Muslim, No. 1482); iron rings as a dowry (HR. Bukhari, No. 4697); and the use of iron for medical treatment (HR. Muslim, Book of Greetings, Chapter 73) (Salmah, 2016).

4. History of Metallurgy

Metallurgy is the art, science, and technology related to the extraction, processing, and properties of metals and their alloys. The history of metallurgy reflects the long evolution of human technology, beginning with the simple use of natural metals and progressing to advanced industrial processes based on science and high technology. Throughout history, iron has occupied a central position as a marker of a revolutionary phase in human development: the transition from the Stone and Bronze Ages to the Iron Age.

4.1 The Metal Age and the Iron Revolution

The Metal Age began when humankind mastered the smelting of copper 7,000 years ago. The subsequent extraction of copper from copper-bearing ore and its alloying with tin to produce bronze (which is harder than copper) was discovered independently by cultures in the Old World and the New World, ushering in the Bronze Age in the ancient Near East around 3500 BCE (Denton, 2022). The Old World refers to regions in Southeastern Europe (Serbia), Southwest Asia (the Middle East), and South Asia (Mehrgarh, Pakistan), where the use of copper as a metal was first discovered, while the New World refers to regions that had not yet adopted it or had not even experienced a Copper Age, such as Indonesia and Southeast Asia (which jumped directly from the Stone Age to the Bronze Age) (Sofian, 2021). The Ancient Near East during the Bronze Age refers to the fertile regions of Southwest Asia, such as Mesopotamia (the Tigris and Euphrates Rivers), the Nile Valley (Egypt), the Levant (Syria-Palestine), Anatolia (Turkey), and parts of the Arabian Peninsula from around 3000–1200 BCE, where the great civilizations of Sumer, Akkad, Babylon, Assyria, New Kingdom Egypt, and the Hittites developed intensive agriculture, writing systems, city-states, written laws, astronomy, mathematics, and the widespread use of bronze (Nuraini, 2020).

Relatively soft metals such as gold and silver were first known around 6000 BCE. However, they were rarely found in a pure form durable enough for heavy tools or weapons. Around 3300–1200 BCE, humans began mixing copper with tin to form bronze, which is stronger and more durable. This period is known as the Bronze Age, as discussed above.

The process of making metal products is a lengthy one. There are at least five stages involved in metal production: mining the *ore*, preparing *the ore* for smelting, smelting *the ore* into *ingots*, casting the metal from *the ingots*, and the final stage, which is the finished product. Based on production techniques, metalworking can be divided into two categories: casting and forging (Sofian, 2021).

Iron was found in the form of meteoritic iron or native iron, which was processed by the Gerzea Egyptians in the fourth millennium BCE, the Anatolian tribes in the third millennium BCE, the Chinese of the Zhou dynasty in the first millennium BCE, the Hopewell Indians, and, more recently, the Greenland Eskimos. However, a breakthrough came when humans began to understand how to process iron ore in the form of oxide minerals (hematite, Fe_2O_3 ; magnetite, Fe_3O_4 ; and limonite, $\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$), carbonates (siderite, FeCO_3), and sulfides (pyrite, FeS_2) (Pilchin & Eppelbaum, 2006) through high-temperature smelting techniques that enabled the reduction of iron oxides into metallic iron. The Iron Age began between 4000 and 2000 BCE. In the 18th century BCE, iron was used for jewelry in the city of Babylon on the banks of the Euphrates River (Wertime, 1964). Around 1500 BCE, iron ore processing developed in the regions of Anatolia (Turkey) and Mesopotamia, and later spread to Egypt, Greece, Cyprus, and India (Wertime, 1973). By 1000 BCE, the Iron Age had reached China, and by around 400 BCE, it had reached England and Nigeria. North and South America, as well as Australasia (a term for the region in Oceania that includes Australia, New Zealand, and the surrounding

islands in the Pacific Ocean), acquired their knowledge of iron processing through European colonization, which began around the 15th century CE.

Iron has a high melting point ($\pm 1537^\circ\text{C}$) (Balley, 1967), making it difficult to process initially. Early iron smelting technology used simple clay *furnaces* with the aid of natural airflow or *bellows* to raise the temperature. The initial product was *bloom iron*, which still contained *slag* and needed to be re-forged to become a solid metal.

The invention of the *blast furnace* in China around the 8th century BCE marked the next revolution in iron metallurgy. Archaeologists discovered the oldest cast iron artifacts in Jiangsu, China (Nanda, 2025). This iron metallurgy technology enabled the production of iron on a large scale and paved the way for mass production of steel, although the quality at that time still varied greatly.

4.2 The Role of Islamic Civilization

The Crusades left a valuable “legacy” for Europe: they adopted scientific knowledge from Muslims, who possessed a superior civilization at the time. They emulated industrial knowledge and skills in the fields of textiles, dyeing, ports, mining, and glass (Syauqi et al., 2016). The following outlines the role of Islamic civilization, particularly the contributions of Muslim scientists to the development of metallurgy and the supporting basic sciences (physics and chemistry).

The metallurgical industry experienced rapid development during the golden age of Islamic civilization (8th to 14th centuries CE), supported by chemists. Chemistry is the primary foundation of metallurgy. Muslim chemists employed meticulous methodology, observation, experimentation, and documentation—unlike the Greeks, who produced only hypotheses. A chemical revolution was spearheaded by Abu Musa Jabir bin Hayyan Al-Azdi (721 CE – 815 CE), whose quantitative experiments led to a series of discoveries in chemical processes—such as the distillation of alcohol, crystallization, the calcination of limestone, and sublimation—culminating in the establishment of the perfume industry. Abu Bakr Muhammad bin Zakariya ar-Razi (864 CE – 930 CE), who classified natural substances. Soda and tin oxide were among his creations. Al-Razi was a pioneering scientist who created the modern laboratory. Through his work, the pharmaceutical industry emerged in the world (Noryani, 2022).

Abdullah Muhammad bin Musa al-Khwarizmi (780 CE – 850 CE) was a Muslim mathematician (algebra, the concept of zero, decimal numbers, and trigonometry) whose work laid the foundation for physics, chemistry, geography, navigation, and astronomy. Al-Khwarizmi devised solutions for linear and quadratic equations that formed the basis of modern calculus and analysis. Al-Khwarizmi created a detailed world map based on geographical calculations. Al-Khwarizmi also developed systematic methods that formed the basis for the development of modern algorithms used in computer programming (Aziza & Rafi'i, 2025).

Abū Yūsuf Ya‘qūb ibn Ishāq aṣ-Ṣabbāḥ al-Kindī (801 CE – 876 CE) classified sword steel into two main categories: ferrous steel and non-ferrous steel. Al-Kindī divided ferrous steel into two groups: carbon steel and wrought iron. He then stated that from these two, a third type of steel was produced, known as composite steel (*murakkab*), “whose quality stems from the combination of masculine and feminine properties—hardness and toughness ” (Al-Hassani, 2018).

Badi' al-Zaman Abu al-'Izz ibn Isma'il ibn al-Razzaz al-Jazari (1136 CE – 1206 CE), a 12th-century Muslim engineer, invented various metal-based mechanisms, such as metal casting in closed molds using green sand, iron gears, metal water pumps, hand-washing devices (wudhu machines), crankshafts in engines, precise hole calibration, laminated wood to reduce warping, static wheel balancing, the use of paper models for design, and water clocks made of iron and copper. This demonstrates that metallurgy was not merely functional but also touched upon aspects of precision engineering and innovation. Al-Jazari's works and his book hold an important place in the history of automata, mechanics, mechatronics, automatic control, robotics, and automatic musical theater (Uzun & Vatansever, 2008). Al-Jazari, referred to as the “Father of Robotics (Aziza & Rafi'i, 2025), is considered the first designer of humanoid robots (cybernetics). One of Al-Jazari's works is the mechanical pump depicted in Figure 2 below.



Figure 2: Al-Jazari's mechanical pump (Uzun & Vatansever, 2008)

Muslim scientists were not merely a bridge between Greek and European civilizations, but offered a scientific paradigm oriented toward the search for divine truth (*al-haqq*) and universal benefit (*maslahah*). Bayt al-Hikmah (during the Abbasid Dynasty) served as a madrasah, observatory, and large library. They translated intellectual works from Greece, Persia, and India into Arabic. However, these Muslim scientists and scholars did not stop at translation alone; they also developed new theories and methods across various scientific disciplines, including astronomy, mathematics, medicine, and chemistry (Putra & Mujab, 2025).

Hezârfen Ahmed Çelebi (1609 CE – 1640 CE) was a scientist, inventor, chemist, astronomer, physician, Andalusian musician, and Arabic-language poet. He brought about revolutionary changes in the fields of astronomy and engineering. Mostafa Al-Sayed (born 1933 CE) was an expert in physical chemistry, nanotechnology, spectroscopy, nanoscience, and biophysics.

Abdul Qadeer Khan (1936 CE – 2021 CE), a Pakistani nuclear physicist and metallurgical engineer. He is known as the “Father of Pakistan’s Nuclear Weapons Program (Fahim, 2016).

Abul-Rihan Al-Biruni (973 CE – 1048 CE) established the correlation between the densities of various metals, including gold, mercury, lead, silver, bronze, copper, brass, iron, and tin (Khan, 2023).

Bacharuddin Jusuf (B.J.) Habibie (1936 CE – 2019 CE) was an expert in aircraft construction and design. Habibie actively conducted various research projects that yielded a number of internationally recognized theories in the fields of thermodynamics, construction, and aerodynamics, such as *the “Habibie Factor,” “Habibie Theorem,”* and *“Habibie Method.”* Habibie pioneered the *Crack Progression Theory*, a mathematical model for predicting crack propagation behavior in aircraft structures down to the atomic level. This theory successfully calculates the location and size of cracks in aircraft structures, allowing crack points to be predicted earlier. This makes aircraft maneuvers safer, reduces the risk of sudden failure, and makes maintenance cheaper and easier. This discovery represents a breakthrough in the world of aviation, earning him the nickname “Mr. Crack” (ANRI, 2022). Habibie’s crack propagation theory aligns closely with—and is even strongly integrated into—*failure analysis* in the fields of metallurgy and materials science and engineering. This theory is not a separate concept but rather a reinforcement and practical extension of *fracture mechanics*, which serves as the backbone of *modern failure analysis*, particularly for critical structures such as aircraft.

The history of industry, production, and manufacturing has been distorted by the emergence of the term “Renaissance” (Age of Renewal) in the 14th century – 17. This was followed by the Industrial Revolution in England in the mid-18th to 19th centuries, which was later adopted by France, Germany, the United States, and Japan. Historical propaganda has obscured the role of industrial activities that already existed and spanned from China to Spain during the Muslim Civilization (approximately 700–1700 CE), a period often referred to as the “Dark Ages” or “Middle Ages,” beginning with the fall of the Roman Empire in 450 CE. Industrial manufacturing—relying on wind- and water-powered machinery—had existed for nearly ten centuries before the 18th-century British Industrial Revolution. Between 700 and 1700 CE, Muslim industrial production ranged from mineral mining to the manufacture of goods through complex processes. Large quantities of metal were smelted in the Muslim world for both local and foreign markets. During the Abbasid Caliphate, manufacturing flourished in Iraq. The mining industry thrived, with Algrava renowned for its gold and silver mines. Mines in Spain yielded gold, silver, tin, copper, iron, lead, alum, sulfur, and mercury. Metallurgy flourished throughout Spain, particularly in Córdoba, known for its iron and lead. The steel industry in Toledo (Spain) was established by Muslims. Murcia was famous for its iron and brasswork. The art of steel and metal inlay, as well as gold and silver work and decorative patterns, was introduced from Damascus (Al-Hassani, 2018).

4.3 The Industrial Age and the Modern Era

The Industrial Revolution of the 18th and 19th centuries was marked by a growing demand for iron and steel. Figures such as Sir Henry Bessemer (1813–1898), a British metallurgist (Spoerl, 2024), discovered a process for converting pig iron into steel quickly and economically. This spurred the mass construction of infrastructure: railroad tracks, bridges, high-rise buildings, and industrial machinery.

From the early 20th century to the present, metallurgy has evolved into a scientific discipline. With advances in metallography, thermodynamics, and materials engineering, humans are now

able to design superalloys, smart metals, and nanostructured metals for aerospace technology, medicine, and sustainable energy.

5. Metallurgy as Art, Science, Technology, and Industry

Metallurgy is not merely an engineering discipline but also embodies the integration of art, science, technology, and industrial activity. These four dimensions make metallurgy a bridge between theoretical thought and practical application, as well as between the cultural heritage of the past and the innovations of the future. In the context of iron, metallurgy has played a role in shaping the face of human civilization, from the exquisite Damascus swords to the steel structures of today's skyscrapers.

5.1 Metallurgy as an Art

Before evolving into a branch of engineering, metallurgy emerged as a traditional metalworking craft that preserved and developed the arts of forging, engraving, and metal forming. In Islamic history, the art of blacksmithing flourished with calligraphic and geometric motifs and a high level of aesthetic refinement, particularly in the form of swords, mosque doors, and household items made of wrought iron and Damascus steel. The beauty of the Zulfiqar sword blade, or the engraved designs on steel from the Persian and Andalusian civilizations, serves as evidence that metallurgy is not merely a matter of material strength but also an artistic expression. Zulfiqar is the name of the Prophet Muhammad's (peace be upon him) sword. This sword was later given to Ali (may Allah be pleased with him), who frequently used it on the battlefield, and it eventually came to be regarded as a symbol of Ali (may Allah be pleased with him). Zulfiqar is a double-edged sword, like ancient Arab swords. Its history is now unclear. The original sword has not been found, and only replicas exist for exhibition purposes, though the degree of their similarity to the original cannot be confirmed (Nizar, 2011). One imagined depiction of a Zulfiqar sword replica is shown in Figure 3 below.



Figure 3 Artistic rendering of a replica of the Zulfiqar sword (Sayed, 2024)

Zulfiqar has evolved into one of the oldest iconographic motifs in the visual arts, appearing on royal and battle flags in Turkey and Iran. The Zulfiqar motif is also found in three types of Nusantara art artifacts: flags, batik textiles, and cannons. Geographically, these artifacts have been found in Aceh, North Sumatra, Jambi, Siak, Selangor, Riau, Johor, Terengganu, Cirebon, Brunei, Central Kalimantan, East Kalimantan, and Sulu (Nizar, 2011).

5.2 Metallurgy as a Science

As modern science has advanced, metallurgy has evolved into a systematic science that studies the microscopic and macroscopic properties of metals. The science of metallurgy is divided into three main branches: (1) physical metallurgy, which examines the structure, mechanical properties, phase transformations, and crystallography of metals; (2) extractive metallurgy, which focuses on the process of separating metals from their ores; and (3) mechanical metallurgy, which studies plastic deformation, metalworking, and the strength and toughness of alloys.

The history of metallurgy records that the Damascus Sword is a high-tech steel sword from the Middle East that is legendary for its sharpness, strength, and unique water-like pattern (a wavy surface pattern). It is made of Wootz steel, a rare high-carbon steel likely originating from Central Asia or Southern India. This sword is capable of splitting silk or stone in a single swing, cutting through another sword without becoming dull, and piercing thick armor. The shape of the Damascus sword is shown in Figure 4 below (Somayyeh Karami-Mohajeri et al., 2025).



Figure 4: Damascus Sword

This iconic weapon gained fame when it was used by the Muslim commander Salah al-Din al-Ayyubi (Saladin) during the Third Crusade, particularly during the capture of Jerusalem in 1187 AD. The sword became a symbol of the Muslim army's might, with its manufacturing secrets closely guarded and remaining a mystery to this day. To this day, no one has been able to reproduce the extraordinary characteristics of this steel. Scientists have discovered that the steel contains carbon *nanotubes* and cementite nanowires—a technology only discovered in the late 20th century (Al-Hassani, 2018).

In addition to the Damascus sword, another legendary sword is *the katana*, a Japanese samurai sword made from a special Japanese steel called "*Tamahagane*," which consists of a combination of high-carbon, hard steel and low-carbon, tough steel that requires a high level of craftsmanship to produce. A samurai sword is shown in Figure 5 below (World Steel Association, 2012).



Figure 5: Samurai Sword

This sword is a military weapon that serves as a very powerful and effective cutting tool and is capable of withstanding sudden, intense pressure.

Modern metallurgy now supports the design of advanced materials such as superalloys for jet turbines, amorphous metals, and shape memory alloys (shape memory alloys), which form the basis of medical and aerospace technologies.

In shape memory alloys, after undergoing deformation, the material has the ability to return to its original size and shape after being subjected to appropriate heat treatment. The material “remembers” its previous size and shape. Deformation is typically performed at relatively low temperatures, while the shape memory effect occurs during heating. Materials with these properties include nickel-titanium alloys (Nitinol) and copper alloys (Cu-Zn-Al and Cu-Al-Ni). These materials exhibit thermoelastic behavior, as the deformation is not permanent. The maximum recoverable strain for these materials is approximately 8%. Applications of these “smart materials” (which sense and respond to environmental changes, specifically temperature) include weldless pipe joints, hydraulic lines in aircraft, undersea pipe joints on ships and submarines, eyeglass frames, orthodontic wires for straightening teeth, foldable antennas, greenhouse window openers, anti-scald control valves in showers, women’s underwear, fire *sprinkler* valves, and biomedical applications (such as blood clot filters, self-expanding coronary *stents*, and bone anchors) (William D. Callister & Rethwisch, 2018).

5.3 Metallurgy as a Technology

The oldest metallurgical technology is casting. The first metal products were likely made of lead. Metal parts made of copper through forging (dating back to more than 9,000 BCE) are better known (Głownia, 2017). Until the 18th century, metallurgy was limited to traditional methods of smelting, melting, and processing metals. The spread of this knowledge was not uniform across the globe but depended on a civilization’s ability to create new techniques and utilize existing ones (Tylecote, 1992). Metallurgy transformed into technology when scientific principles were applied to the design of tools, processes, and metal production systems.

One product of metallurgical technology that aids in understanding the solar system is a model of celestial objects known as the Armillary Sphere with a rotating Celestial Globe. Figure 6 below shows an Armillary Sphere with a Celestial Globe made of gold-plated brass, 53 cm tall, and dating from 1713 AD (Antiquariaat FORUM & Antiquariat INLIBRIS, 2021).



Figure 6: Armillary sphere with celestial globe

Metallurgical technology is the practical application of metallurgical science, including (1) physical metallurgy, which involves metallography and heat treatment; (2) extractive metallurgy, which is applied in pyrometallurgical processes (using high temperatures, such as

in smelting and roasting), hydrometallurgy (using aqueous solutions, such as leaching and solvent extraction), and electrometallurgy (using electric current, such as in electrowinning and electrorefining); and (3) mechanical metallurgy, which is applied to metal forming and machining. In addition to the three technologies in these branches, there are technologies related to metallurgy that support the development of metal technologies. These technologies include metal protection (coating, electroplating, electroless plating) and corrosion control; failure analysis; powder metallurgy; welding metallurgy; casting; steelmaking; special steels & superalloys; surface engineering; and material joining.

Automated welding processes, precision forging, plasma metal coating, and electric arc melting are the result of the integration of materials science, mechanics, and process engineering. In the electric vehicle and renewable energy industries, metallurgical technology supports the production of high-strength lightweight steel, neodymium-based permanent magnets, iron, and boron ($\text{Nd}_2\text{Fe}_{14}\text{B}$), as well as heat storage components based on Fe-Cr-Al alloys.

5.4 Metallurgy as an Industry

As an industry, metallurgy encompasses the entire value chain from mining, metal processing, and component manufacturing to the final product. The iron and steel industry is a major contributor to modern infrastructure, such as roads, bridges, railroad tracks, high-rise buildings, as well as ships and heavy-duty vehicles.

Within the industry, iron and steel are distinguished by their material characteristics, manufacturing processes, and applications. The iron-making process uses smelting furnaces, commonly referred to as furnaces or kilns. One type of furnace used is the blast furnace, shown in Figure 7 below (ASM International, 2008).

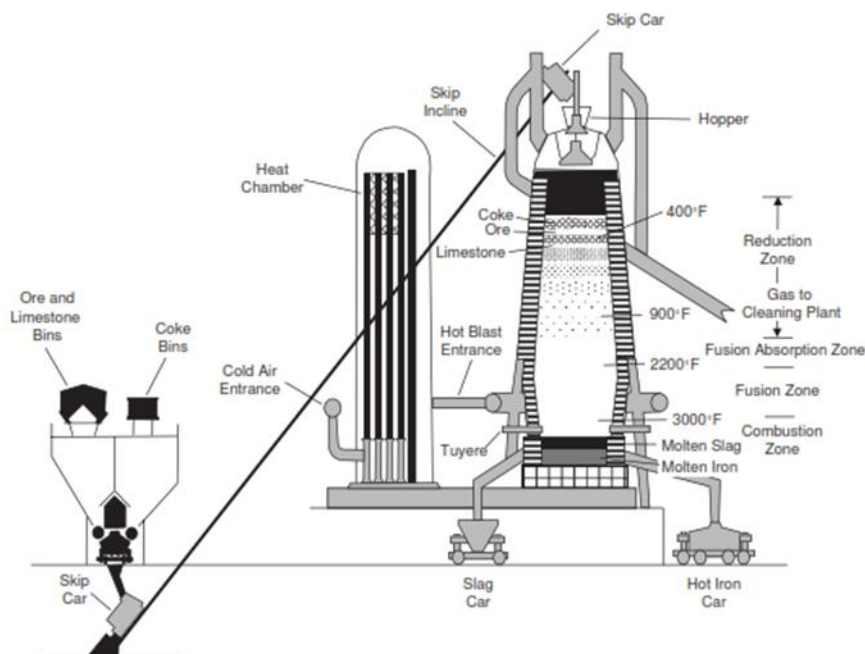


Figure 7 Iron smelting furnace

The iron smelting process uses raw materials such as ore (iron ore) or a mixture of scrap (scrap iron), coke, and limestone. The raw material, which consists of iron oxide minerals, undergoes reduction with the reducing gas, CO. The result of iron smelting is pig iron (molten crude iron) with a carbon content of 4%–5%.

The steelmaking process uses raw materials such as pig iron and/or scrap iron in a steelmaking furnace. The principle of steelmaking is to control the carbon (C) content between 0.05% and 2%, and to adjust the levels of manganese (Mn), silicon (Si), nickel (Ni), chromium (Cr), copper (Cu), tin (Sn), and other elements according to the requirements of the specific steel grade. In addition, there are the processes of dephosphorization and desulfurization—that is, the removal of these two impurities (phosphorus and sulfur)—with the aim of improving the quality and strength of the steel. The steelmaking process developed in 1856 was the Bessemer process, and in 1858, the open-hearth process was developed. In 1948, the Basic Oxygen Furnace (BOF) process began, and in 1900, following the invention of the electric arc, the Electric Arc Furnace (EAF) was developed, marking the shift to modern steel production powered by electricity. The EAF, or electric arc furnace, has a construction as shown in Figure 8 below (ASM International, 2008).

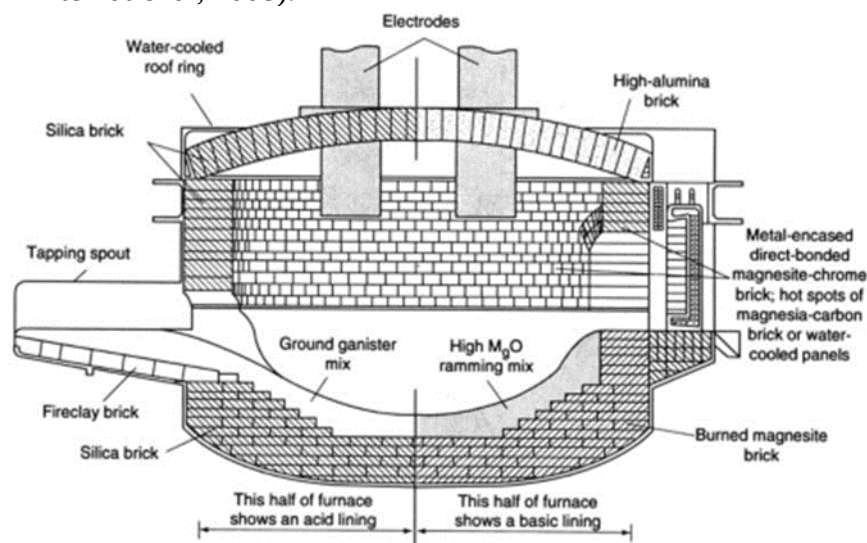


Figure 8: Electric arc furnace for steel production

The EAF can reduce carbon emissions by up to 50% compared to a blast furnace, especially when powered by renewable energy sources. Studies indicate that a transition to EAF-based steel production in Europe has the potential to reduce CO₂ emissions from steelmaking by more than 40% by 2030. An exciting advancement in metallurgy is hydrogen-based steelmaking. This process replaces carbon-based fuels with green hydrogen (as a reducing agent) in steel production, which can reduce CO₂ emissions. The HYBRIT pilot project in Sweden has demonstrated that hydrogen can produce steel with nearly zero carbon emissions (Azanaw, 2024).

According to data from the World Steel Association (2022), the steel industry consumes more than 6% of the world's energy, but it is also a key target in the decarbonization and green technology agenda. Therefore, metallurgy also plays a crucial role in the sustainable energy transition, for example, through the development of hydrogen-based iron smelting processes to reduce carbon emissions.

6. Iron's Contribution to Future Technologies

As we enter the era of the 5.0 industrial revolution and global digital transformation, iron continues to maintain its role as a fundamental metal in supporting future technological advancements. Amid a wave of innovations relying on artificial intelligence (AI), the Internet of Things (IoT), and renewable energy, iron and its alloys—particularly steel—continue to

evolve to meet humanity's technical, environmental, and social needs. High-performance steel alloys have significantly improved material durability and strength, making them more efficient for constructing large and complex structures. They offer the potential to accelerate construction schedules, reduce labor costs, minimize material waste, and contribute to sustainability by optimizing resource use (Azanaw, 2024).

6.1 Steel in Smart Technology and Future Infrastructure

With the growing demand for smart infrastructure—such as earthquake-resistant buildings, smart bridges, and high-speed rail tracks—high-strength lightweight steel (Advanced High Strength Steel/AHSS), particularly HSLA (High Strength Low Alloy) and Ultra High Strength Steel (UHSS), has become the top choice. These types of steel, based on iron alloys containing carbon, manganese, and boron, possess ultra-high tensile strength (>1000 MPa) while remaining lightweight, thereby reducing energy consumption and transportation costs. HSLA and UHSS are used in high-rise buildings, long-span bridges, and critical infrastructure, where performance and durability are paramount. For example, the use of UHSS in the construction of skyscrapers such as the Jeddah Tower has enabled the achievement of unprecedented heights while ensuring stability against extreme winds and earthquakes (Azanaw, 2024).

In the architecture of the future, modular steel structures enable rapid construction, high recyclability, and adaptive flexibility to changes in a building's function. These smart structures are designed to enhance the resilience, sustainability, and efficiency of infrastructure (Albzaie, 2024; Narayanan, 2025). With this system, steel is no longer used merely as a physical backbone but also as a medium for connectivity, sensor integration, and smart automation.

6.2 Steel in Eco-Friendly Vehicles

The future of the automotive and transportation industries relies heavily on iron alloys for the development of electric vehicles and low-emission mass transit. Iron serves as the primary material in: (1) lightweight and safe vehicle frames; (2) electric motor housings and cooling systems; and (3) the production of permanent magnets based on neodymium-iron-boron (NdFeB) alloys. The automotive industry has long relied on steel to ensure vehicle safety, performance, and durability. However, in recent years, the demand for more efficient, lightweight, and strong materials has led to an increase in the use of Advanced High-Strength Steel (AHSS) alloys. This steel is engineered with specific alloying elements, such as carbon, manganese, and chromium, to achieve superior mechanical properties. AHSS has revolutionized the way automotive manufacturers design vehicles, offering a unique combination of strength, formability, and lightness that traditional steel cannot provide (Jalloh, 2025).

The properties of steel, including its durability and recyclability, make it vital to modern society. The steel industry must be committed to producing products that utilize processes achieving environmental, social, and economic sustainability. The production of materials (steel) can account for a significant portion of a vehicle's overall life-cycle emissions, as assessed by a life-cycle assessment (LCA), as illustrated in Figure 9 below (AISI, 2020).

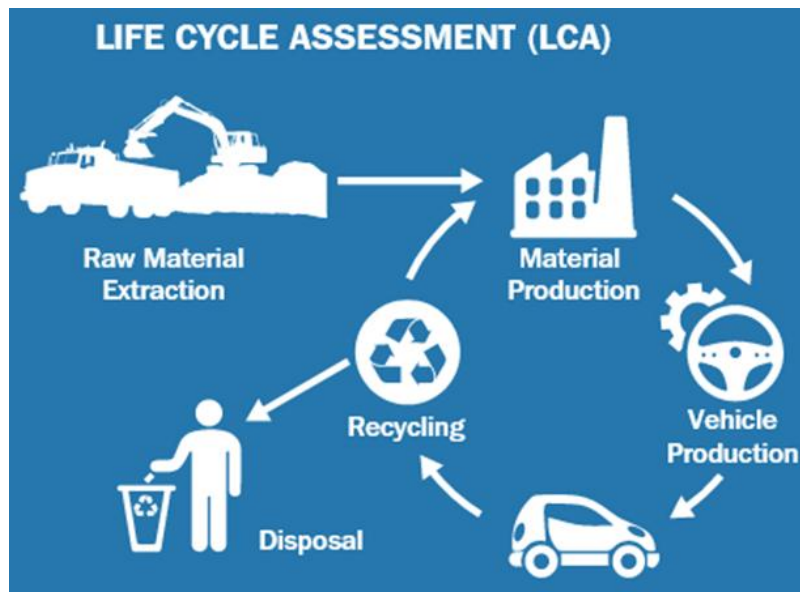


Figure 9: Vehicle LCA

An LCA study shows that reducing vehicle weight with AHSS compared to aluminum will result in a reduction of 300 million metric tons of greenhouse gas (GHG) emissions by 2038, equivalent to the emissions produced by burning 45 billion gallons of gasoline. By 2053, an additional 100 million metric tons will be saved, bringing the total GHG emissions savings to over 400 million metric tons. Therefore, when considering the vehicle's life cycle, steel is the most environmentally effective choice due to its lower energy intensity and emissions during the manufacturing phase, significant mass reduction during the driving phase, and recyclability at the end of the vehicle's life. Material production accounts for up to 30 percent of total GHG emissions in internal combustion engine (ICE) vehicles and as much as 47 percent in battery electric vehicles (BEVs). Steel production generates significantly lower CO_2 emissions compared to other body materials such as aluminum, magnesium, and carbon-based plastics.

Steel is a vital material in most vehicles and will continue to play a dominant role in the future due to its excellent mechanical properties. Steel meets the key criteria for material selection: stiffness, strength, fatigue resistance, formability, impact resistance, cost-effectiveness, recyclability, and weight reduction. Steel excels in terms of easy availability and an economical price-performance ratio (Singh, 2016).

6.3 Iron in Medical Technology and Bioengineering

The fusion of engineering with biology and medicine is biotechnology and biomedical engineering. Biomedical engineering focuses on the development of medical devices, biomaterials, and new technologies. In addition to biomaterials, iron alloys also play a role in the future of healthcare and bioengineering, including stainless steel (Dahi et al., 2025).

Biomaterials are natural or synthetic materials used to create implants to replace lost or damaged biological structures in order to restore form and function. Biomaterials intended for long-term use, such as orthopedic implants, require good physical and chemical stability, such as stainless steel and titanium alloys (Wang et al., 2022). Biodegradable iron-based metal implants gradually dissolve in the body without causing toxic reactions.

Magnetic iron nanoparticles (MnFe_2O_4) are used for precise drug delivery, cancer therapy with hyperthermia, MRI (Magnetic Resonance Imaging), as well as therapeutic and diagnostic

applications (theranostics) (Ilhami, 2016). With advances in bio-nanotechnology, iron-based materials will enable the emergence of smart medical systems, such as in-body sensors and continuous health monitoring devices.

6.4 Iron in the Energy Transition and Green Technology

The energy transition refers to the shift from low-efficiency energy sources to high-efficiency energy sources. Looking back at history, human society has undergone two energy transitions: from the era of firewood to the era of coal, and finally to oil. The most recent phase of the energy transition involves a shift from carbon-based energy—primarily coal and oil—to low-carbon energy sources such as natural gas, wind, solar, and hydropower. The shift toward renewable energy sources requires a transition of the entire energy system, with significant social, economic, and ecological consequences that extend far beyond the energy sector (Yang et al., 2024).

Steel production consists of primary and secondary production processes. Approximately 90% of primary production is carried out using blast furnaces (BF), followed by basic oxygen furnaces (BOF), which account for about 70% of global steel production. An alternative method is the direct reduced iron electric arc furnace, which differs in the type of iron ore used, the state of the material during reduction, the primary reducing agent, and the energy input balance. Secondary steel production is carried out through two main routes: (i) BOF, which uses molten iron from the BF and steel scrap, and (ii) electric furnaces (EF), which can use up to 100% steel scrap, accounting for 30% of steel demand. Secondary steel production requires large amounts of electricity. The steel production routes from 1900 to 2015 that generated greenhouse gas emissions are illustrated in Figure 11 below (Guitar et al., 2025).

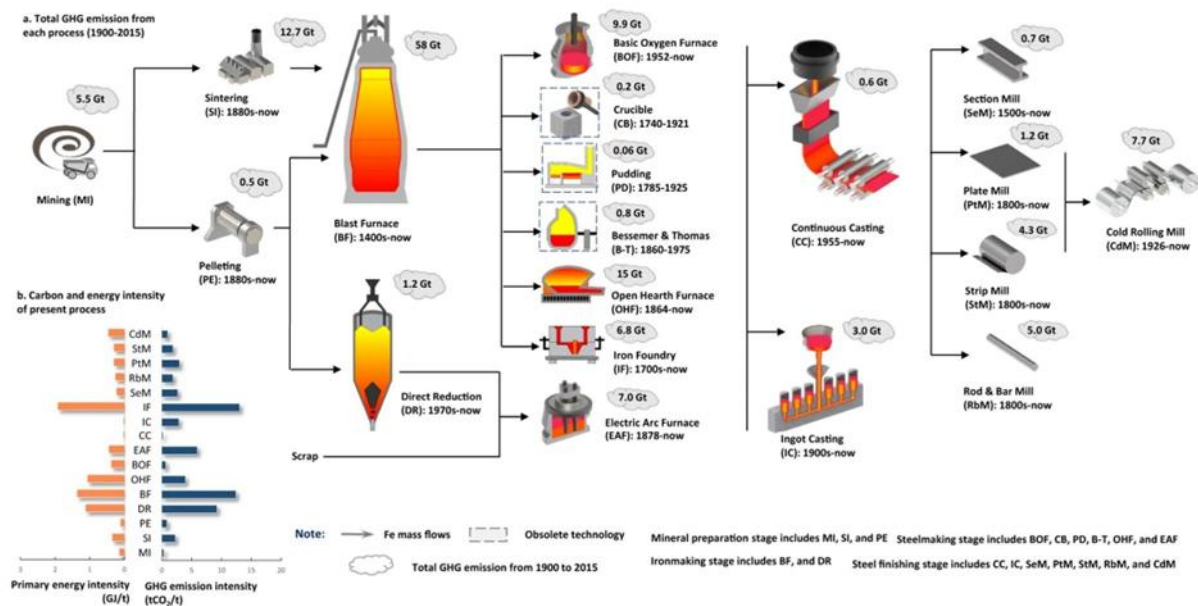


Figure 11 Steel production (1900–2015) with *greenhouse gas emissions*

In the global agenda toward net-zero emissions, iron is part of the solution through innovations such as the following. Decarbonization of the steel sector occurs simultaneously and in parallel with the energy transition in the economy (Durga et al., 2024). The use of low-carbon technologies and renewable energy sources in the steel industry, known as Green Steel, aligns with the principles of the Circular Economy, as it is environmentally friendly, leads to increased resource reuse, reduces waste, and lowers the carbon footprint during production.

Green steel is steel produced using methods that significantly reduce carbon emissions—even without fossil fuels—and utilize renewable energy such as green hydrogen or innovative technologies like EAFs powered by renewable energy. Green steel technology, combined with the principles of the circular economy, can enable sustainable development. The steel industry can also contribute to economic growth and protect the environment by ensuring the optimal use of resources, increasing recycling, and adopting new low-emission production technologies (Das & Maji, 2025).

The adoption of technology has negative consequences for the environment and society. Therefore, green or clean technology is needed. This new technology takes into account the impact of innovation on the environment, both in the short and long term. Energy efficiency, recycling, safety and health issues, renewable resources, and other factors are covered by green technology (Kumar, 2020).

Steel is a well-established base material and one of the most environmentally friendly mass-produced products due to its high recyclability and the relatively low amount of energy required for its production. Steel production plays a role in the implementation of green technology through green manufacturing, which produces products using materials and processes that minimize negative environmental impacts, help reduce greenhouse gas emissions, conserve energy and natural resources, enhance safety for consumers, the public, and employees, and improve organizational profitability. Green manufacturing in steel production involves the use of renewable energy systems and clean technology equipment, reducing pollution and waste by minimizing the use of natural resources, recycling and reusing waste, and cutting emissions. The carbon-free smelting process uses hydrogen as a reducing agent. Scrap iron is recycled to increase the local content of steel production, reduce energy consumption, and lower carbon dioxide emissions. Steelmaking slag is utilized as a base course material in road construction and other civil engineering projects, as a calcium oxide-based reformer (for soil improvement), and as a raw material for cement and fertilizers due to its excellent properties and functions (Tiwari et al., 2017).

7. Conclusion

Iron is not merely a chemical element with atomic number 26 on the periodic table. From the perspective of Islam and modern science, iron symbolizes strength, utility, and the responsibility of civilization. Its explicit mention in the Qur'an indicates that iron is not merely a strategic material but also a “verse of creation” (ayat kauniyah) containing theological, philosophical, and ethical messages. Through the hadiths of the Prophet Muhammad, we see how iron was used wisely in the contexts of self-protection, defense, and development.

From historical and scientific perspectives, iron metallurgy (including steel) has been a cornerstone of civilizational progress. Iron remains the backbone of future technology. From electric vehicles, clean energy systems, and precision medical technology to smart architecture, iron is transforming from a mere structural material into a multifunctional and high-value material.

This article argues that the integration of revelation and science is not a contradiction but rather a synergy that must continue to be pursued. Muslims must not merely be users of technology, but also producers and developers of science and technology, as well as guides, facilitators, and guardians of values in scientific and technological innovation, including in the field of metallurgy. This article is intended as a small contribution toward fostering a technological

paradigm that is not only oriented toward efficiency and profit but is also rooted in transcendental values that shape the whole human being.

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