Contemporary Thoughts Press

Journal of Interdisciplinary Qur'anic Studies

Shahid Beheshti University

Journal of Interdisciplinary Qur'anic Studies Vol. 4, Issue 2, December 2025, Pages 211-223

A Metallurgical Re-evaluation of Dhū al-Qarnayn's Barrier: From the Alloy Hypothesis to an Fe-Cu Composite Model

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Article History: Received 7 September 2025; Accepted 4 November 2025

ABSTRACT:

Original Paper

The construction of the barrier by Dhū al-Qarnayn, as depicted in Surah al-Kahf (Q. 18:96), involves a unique combination of iron and copper. Traditionally, this process has been interpreted as the formation of a homogenous metallurgical alloy. However, from the perspective of materials science, this "Alloy Hypothesis" faces severe technical challenges, including the extreme melting point of iron and the inherent immiscibility of the iron-copper (Fe-Cu) system. This study employs a multidisciplinary methodology, combining Qur'anic analysis with historical metallurgical data from the Achaemenid era (6th century BCE) as a representative technological baseline. We argue that the barrier was not a product of anachronistic alloying but rather a masterpiece of composite engineering. By introducing a "Composite Model" based on interfacial thermal bonding and capillary infiltration, we demonstrate how ancient engineers could achieve structural unification (*radm*) and corrosion resistance without violating the physical laws of thermodynamics. Our findings suggest that the use of copper as a low-temperature intermediary binder provided a feasible solution for creating an impenetrable, monolithic barrier within the technological constraints of antiquity.

KEYWORDS: Qur'anic engineering, Dhū al-Qarnayn's barrier, Scientific interpretation, Archaeometallurgy, Iron-Copper System, Composite Materials, Achaemenid Metallurgy, Interfacial Bonding.

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http://dx.doi.org/10.37264/JIQS.V4I2.9 https://iqs.sbu.ac.ir/article_106982.html?lang=en

1. Introduction

The narrative of Dhū al-Qarnayn in Surah al-Kahf stands as one of the most remarkable and multi-layered accounts in the Qur’an. For centuries, this story has sparked deep inquiry across numerous dimensions, including, but not limited to, the historical identity of Dhū al-Qarnayn, the nature and origin of the tribes of Gog and Magog (Yaʾjūj and Maʾjūj), and the means (*asbāb*) of his global travels (van Donzel & Schmidt 2010). Among these varied aspects, the Barrier (*al-Sadd*) has remained a central point of fascination, encompassing two distinct areas of research: its geographical location and its unique technical construction.

The quest for the barrier’s location has historically garnered significant interest; a notable example is the journey of the Abbasid explorer Sallām al-Tarjumān around 842 CE, who was commissioned by Caliph al-Wāthiq bi-llāh specifically to locate the structure (van Donzel & Schmidt 2010). While efforts like Sallām’s sought to identify its physical remains, the methodology of its assembly has received less analytical attention. The Qur’anic account (Q. 18:96-97) depicts a precise engineering sequence:

> آتُوني زُبَرَ الْحَديدِ حَتَّى إِذا ساوى بَيْنَ الصَّدَفَيْنِ قالَ انْفُخُوا حَتَّى إِذا جَعَلَهُ ناراً قالَ آتُوني
> أُفْرِغْ عَلَيْهِ قِطْراً * فَمَا اسْطاعُوا أَنْ يَظْهَرُوهُ وَ مَا اسْتَطاعُوا لَهُ نَقْباً (الكهف/*96-97*)
>
> *“Bring me pieces of iron!” When he had levelled up between the flanks, he said, “Blow!” When he had turned it into fire, he said, “Bring me molten copper to pour over it” (96). So they could neither scale it, nor could they make a hole in it (Q. 18:96-97).*

Dhū al-Qarnayn reached a region between two mountain slopes (*al-ṣadafayn*) and requested the inhabitants' physical labour and power (*quwwah*). The construction involved stacking massive iron blocks (*zubar al-ḥadīd*) until they levelled the gap between the mountains. He then applied heat until the iron reached a state of incandescence (*nār*), followed by pouring molten copper (*qiṭr*) over the assembly. The resulting barrier was described as a massive, unified structure that the adversaries could neither scale, due to its height and smoothness, nor pierce, implying a monument of immense structural continuity.

Traditionally, this iron-copper construction has been interpreted as the creation of a homogenous metallurgical alloy (Moghaddasi 2022). However, the feasibility of such a process, producing a unified alloy on such a monumental scale, requires a detailed investigation into materials science and the historical technology available in antiquity. This paper aims to conduct a technical evaluation of these claims, specifically examining the metallurgical prerequisites of the iron-copper (Fe-Cu) system and the thermal constraints of ancient engineering.

By establishing a historical baseline in the 6th century BCE (the Achaemenid era), we investigate the "Alloy Hypothesis" against documented technological constants. Following this evaluation, we propose a "Composite Engineering Model" based on interfacial bonding. This model offers a detailed technical explanation of how copper and iron could interact to form a unified structure, providing a new perspective on how such a barrier could be realized within the framework of ancient engineering principles.

2. Theoretical Framework and Historical Context

2.1. Technological Baseline and Chronological Reference

The technical evaluation of Dhū al-Qarnayn's barrier requires a stable historical reference point to define the boundaries of ancient engineering. For the purposes of this study, we adopt the hypothesis proposed by Tabataba'i (1996, 13: 391), which identifies Dhū al-Qarnayn as Cyrus the Great (6th century BCE). This selection provides a concrete chronological setting for assessing available materials and techniques.

However, it is crucial to note that the specific historical identity, whether Cyrus or another figure from the same broad era, does not fundamentally alter the metallurgical core of this research. This is due to the prolonged stability of ancient technology; during this period and for centuries thereafter, the rate of innovation in thermal processing was relatively slow. The technological ceiling of that era remained essentially static regarding iron smelting and fusion techniques. Consequently, the engineering arguments presented in this paper remain valid across a wide chronological window. A more rigorous analysis of these technological constants, and the reasons they preclude modern industrial methods, will be detailed in the following sections.

Having established this historical baseline, we must now examine the specific metallurgical boundaries of the Achaemenid period to distinguish the feasible from the impossible in ancient construction.

2.2. Historical Context and Archaeological Absence

The identification of Dhū al-Qarnayn with Cyrus the Great (6th century BCE), following Tabataba'i's hypothesis, is adopted primarily as a technological baseline rather than a definitive historical attribution. Metallurgical capabilities based on bloomery iron production, characterized by a practical temperature ceiling of approximately 1100–1300°C, remained largely stable for several centuries across the ancient Near East and neighbouring regions. Therefore, the core engineering arguments of this study remain valid even if the barrier is attributed to a slightly earlier or later period.

Furthermore, the location of the barrier is not necessarily limited to the Achaemenid heartland. Considering the empire's vast frontiers and the Qur'anic description of remote mountain passes (*al-ṣadafayn*), the structure could plausibly be situated in peripheral mountainous zones such as the Caucasus, Central Asia, or other frontier regions where systematic archaeological surveys remain incomplete.

The absence of definitive archaeological remains does not negate its existence. A barrier of limited length, likely no more than a few hundred meters, could readily have been concealed by millennia of alluviation, landslides, and sediment accumulation in a mountain pass environment. The Qur'anic text emphasizes that the barrier could neither be scaled nor pierced (Q. 18:97), which is consistent with its potential burial under natural geological processes without structural failure.

This multidisciplinary study, therefore, focuses on the engineering feasibility of the described construction, offering a plausible composite model that is fully consistent with the technological capabilities of the era.

3. Technological Constraints and the Engineering Problem

The construction of the barrier, as detailed in the Qur'anic narrative, involves the manipulation of massive quantities of iron, referred to as *zubar al-ḥadīd* (literally massive pieces or blocks of iron). The process describes the application of heat until these masses reach a state of *nār* (translated as fire, here implying a glowing, incandescent thermal state). From an engineering perspective, the primary challenge lies in the integration of these discrete blocks into a single, unified *radm* (a term denoting a stacked, reinforced, and tightly packed structure).

3.1. The Metallurgical Complexity of the Iron-Copper System

To evaluate the feasibility of the Alloy Hypothesis, it is necessary to examine the fundamental materials science of the Iron-Copper (Fe-Cu) system. According to the Springer Materials Database, iron and copper are characterized by a significant lack of solid solubility. The iron-copper system consists of alloys and mixtures that are immiscible in the solid state, meaning they do not form a continuous solid solution, but rather exist as separate phases within the material. This immiscibility is due to the pronounced differences in their crystal structures, iron being body-centered cubic (BCC) and copper being face-centered cubic (FCC), and their atomic sizes (Springer Materials n.d.).

This inherent immiscibility poses a severe engineering challenge. Even if the temperature were raised to the melting point of iron (1538°C) to achieve a liquid state, the challenge of homogenization would remain unresolved. Due to the metastable miscibility gap in the liquid phase, the two metals tend to separate like oil and water. In a large-scale construction like a barrier, this leads to gravitational segregation, where the denser iron-rich phase settles at the bottom, while the copper-rich phase floats toward the surface, preventing the formation of a unified, high-strength alloy.

Furthermore, as highlighted by contemporary research (Sun 2020), producing high-performance Fe-Cu alloys with a uniform dispersion of phases requires advanced industrial preparation techniques that were non-existent in antiquity. These include:

Vacuum Induction Melting: To prevent oxidation and ensure compositional stability.

Upward Continuous Casting: To manage the solidification process and minimize defects.

Laser-based 3D Printing or Air Atomization: To achieve a fine-scale distribution of iron within the copper matrix.

Therefore, the validity of any construction theory depends not only on chemical possibility but also on its scalability. We must now critically analyse whether the technological framework of the 6th century BCE could support such extreme thermal, chemical, and structural demands.

3.1.1. Metallurgical and Engineering Prerequisites

To evaluate the feasibility of any unification theory regarding the barrier, it is necessary to examine the fundamental materials science of the iron-copper (Fe-Cu) system and the mechanics of thermal joining. Historically and scientifically, creating a monolithic structure of this magnitude would necessitate fulfilling the following rigorous prerequisites:

3.1.1.1. Chemical and Phase Homogenization

If the barrier is interpreted as a homogeneous alloy (Moghaddasi 2022), it must overcome the inherent immiscibility of the Fe-Cu system. According to the Springer Materials Database, the iron-copper system consists of alloys and mixtures that are immiscible in the solid state. This immiscibility is due to the pronounced differences in their crystal structures (BCC iron vs. FCC copper) and their atomic sizes (Springer Materials n.d.).

To prevent gravitational segregation (where denser iron settles at the bottom), modern industry requires vacuum induction melting or upward continuous casting (Sun 2020). Any model of the barrier must account for how this atomic-level integration was managed without such advanced infrastructure.

3.1.1.2. Large-Scale Fusion and Thermal Joining

If the model assumes that the iron blocks (*zubar al-ḥadīd*) were joined through fusion welding or a monolithic thermal bond to form a *radm*, the following infrastructure is required:

Uniform Heat Saturation: To achieve a welded or fused state, the entire contact surface of the massive iron blocks must be heated to temperatures near or at the melting point (1538°C).

Surface Cleaning and Fluxing: Fusion joining requires the removal of iron oxides (scales) from the surfaces. Without modern chemical fluxes or a controlled atmosphere, a unified metallurgical bond across thousands of tons of iron is virtually impossible.

3.1.1.3. Geometric and Spatial Scale-Up

The feasibility of these metallurgical processes is strictly bound to the geographical constraints of the site:

The al-ṣadafayn Gap: The term *al-ṣadafayn* (the two mountain slopes) implies a significant gap, often estimated at approximately 30 meters. Maintaining a uniform thermal field across such a vast width to reach the state of *nār* (incandescence) is an unprecedented challenge in energy engineering.

Vertical Load and Containment: The model must explain how ancient engineers managed the hydrostatic pressure and vertical structural load if large portions of the barrier were in a molten or semi-molten state during construction.

3.2. Technological Impossibility and the Historical Deadlock

The technological landscape of the 6th century BCE under Cyrus the Great (r. 559–530 BCE) was dominated by bloomery iron production, a low-temperature process that precluded the large-scale fusion, homogenization, or alloying required for a monolithic Fe-Cu barrier. Bloomery furnaces, the primary method for iron smelting across the Achaemenid Empire and the broader Near East, operated at maximum temperatures of 1100–1300°C, well below the melting point of iron (1538°C) (Tylecote 1992). These furnaces produced spongy iron blooms intermixed with slag, which required extensive hot hammering (smithing) to consolidate the metal, rather than molten iron suitable for casting or the thermal joining of massive blocks (Pleiner 2000).

In contrast, the blast furnace, capable of reaching temperatures over 1500°C in the bosh to produce molten pig iron and low-iron glassy slags, emerged only in post-medieval Europe (post-12th century) and was absent in the ancient Near East (Tylecote 1992). These limitations persisted well into later periods, with no evidence of breakthroughs in high-temperature melting or controlled atmospheres until much later eras (Erb-Satullo 2019). Thus, the prerequisites outlined in Section 3.1, atomic homogenization, fusion welding, and monumental thermal management, far exceeded the capabilities of Achaemenid engineering, rendering such a barrier infeasible without anachronistic modern interventions.

Beyond the limitations of furnace temperature, the physical dimensions of the barrier (e.g., a 30-meter span) presented an insurmountable logistical challenge. In ancient metallurgy, thermal energy was typically localized and transient. To achieve the state of incandescence (*nār*) or to perform fusion welding across thousands of tons of *zubar al-ḥadīd*, an engineer would have needed to:

Sustain a Continuous Thermal Field: Maintaining a uniform temperature exceeding 1000°C across a 30-meter-wide and several-meter-high gap would require a massive, coordinated combustion of fuel that far surpassed the energy density available from charcoal and manual bellows.

Overcome Heat Dissipation: In an open-air mountainous environment (*al-ṣadafayn*), the rate of heat loss to the atmosphere and the surrounding rock would be immense. Without a closed refractory chamber, which is impractical for a 30-meter barrier, the iron blocks would dissipate heat faster than ancient fuel sources could supply it, preventing any meaningful metallurgical bonding or melting.

Manage Structural Loads: If any significant portion of the iron were to reach a semi-molten state for welding or alloying, the hydrostatic pressure and the weight of the overhead blocks would cause the lower sections to deform or collapse, as there is no evidence of large-scale, heat-resistant formwork or support systems in Achaemenid engineering.

The Problem of Bulk Thermal Assembly: Beyond the chemical barriers, the transition from small-scale smithing to macro-scale metallurgical joining introduces the problem of uniform heat distribution. Achieving a simultaneous incandescent state across a 30-meter span, without the benefit of modern thermal insulation, is a logistical impossibility. Modern engineering solutions for joining such massive structural components require highly specialized and complex welding procedures to manage thermal stresses and ensure structural integrity (see Medlock et al. (2019), for the complexity of such operations). The rapid heat dissipation into the surrounding mountain rock, acting as a massive heat sink, would prevent ancient iron blocks from reaching the necessary bonding temperature. This further reinforces the hypothesis that the construction must have relied on a localized, sequential application of molten filler rather than an attempt at monolithic thermal fusion.

As established by the Springer Materials (n.d.) data on the immiscibility of the Fe-Cu system, any attempt at alloying without modern stirring and vacuum technology would result in phase separation and structural failure. Therefore, the Alloy Hypothesis (Moghaddasi 2022) remains a metallurgical anachronism, rendering such a barrier infeasible without the use of modern interventions.

Given these insurmountable thermal and logistical deadlocks, the Alloy Hypothesis fails to provide a viable engineering explanation for the barrier's construction. This necessitates a shift in perspective from metallurgical fusion to a composite structural model. In the following section, we demonstrate how the specific sequence of the Qur'anic narrative describes a sophisticated process of interfacial bonding, which bypassed the thermal ceiling of the ancient world.

4. The Proposed Model: Composite Structure and Interfacial Thermal Bonding

The dismissal of the Alloy Hypothesis leaves two critical engineering questions unanswered: firstly, if the copper was not intended for alloying, what was its specific functional role? Secondly, how were the massive iron blocks (*zubar al-ḥadīd*) integrated into a stable, vertical structure without recourse to large-scale fusion welding? To address these inquiries, we propose a Composite Engineering Model in which copper and iron maintain their distinct material identities while acting in synergy. This model can be analysed through two primary functions:

4.1. Copper as a Protective and Passivating Layer

In the environmental conditions of a mountain pass, an unprotected iron structure would be highly susceptible to rapid oxidation. The choice of copper as a coating material provides a superior electrochemical shield due to the following factors:

Electrochemical Stability: From a thermodynamic perspective, copper possesses a positive standard reduction potential (+0.34 V), making it significantly more noble than iron (-0.44 V) (Skoog et al. 2013). While iron reacts spontaneously with atmospheric oxygen and moisture to form porous, non-adherent oxides (rust), copper is energetically more stable. This potential difference ensures that the copper layer remains intact, acting as a passive barrier that isolates the iron core from corrosive agents.

Self-Passivation: Unlike iron oxide, which facilitates further corrosion by allowing oxygen to penetrate deeper, any initial oxidation of the copper surface forms a dense, stable patina, typically copper carbonates or oxides (Copper Development Association n.d.; Strandberg & Johansson 1998). This thin layer passivates the surface, effectively sealing the structure and ensuring the barrier’s longevity over centuries.

4.2. Copper as a Structural Intermediary (Capillary Infiltration)

The most significant engineering advantage of this model is its circumvention of the 1538°C melting point of iron. Instead, it utilizes the principles of interfacial thermal bonding and capillary infiltration:

The Brazing Effect: While ancient furnaces could not liquefy bulk iron, they could easily sustain the 1085°C required to melt copper (Lucas-Milhaupt n.d.; Way et al. 2020). When molten copper (*qiṭr*) is poured over the iron blocks pre-heated to an incandescent state (*nār*), it gains high fluidity and flows into the microscopic and macroscopic interstices between the blocks.

Gap-Filling and Mechanical Integrity: Through capillary action, the liquid copper fills every void within the iron assembly. Upon solidification, it creates a powerful metallurgical bond at the interface. This transforms a pile of discrete iron masses into a unified, monolithic *radm* (a term denoting a filled-in, voidless structure). It should be noted that while pure capillary action requires narrow clearances, the integration of ancient, irregularly shaped iron blocks would rely on gravity-assisted infiltration and liquid-phase sintering. The molten copper acts as a gap-filling medium that occupies the macroscopic voids between the blocks, while simultaneously utilizing capillary forces to penetrate the microscopic surface roughness of the iron. This dual mechanism ensures a continuous metallurgical bond regardless of the precision of the initial iron masonry, effectively potting the blocks within a solid copper matrix.

Inaccessibility and Resistance: By filling the gaps, the copper prevents the use of levers or mechanical tools by an adversary to dislodge individual blocks (American Welding Society 2025; Harris Products Group n.d.). The resulting composite structure combines the high compressive strength of the iron core with the ductile, sealing properties of the copper matrix, creating a barrier that is both impenetrable and immune to the structural decay typical of dry-stack masonry.

4.3. Modern Applications and Comparative Performance of Fe-Cu Composites

To contextualize the proposed composite model within contemporary materials science, it is useful to examine modern analogues of iron-copper systems, even though the Qur'anic barrier is best understood as a macroscopic composite rather than a homogeneous alloy.

Modern Fe-Cu materials are primarily produced as composites using advanced techniques such as powder metallurgy, mechanical alloying, or brazing, due to the very limited solid solubility in the Fe-Cu system (Raghavan 2004). Typical compositional ranges include:

Low Copper Additions (0.25–0.55 wt% Cu): Widely used in weathering steels (e.g., COR-TEN, ASTM A588) to enhance atmospheric corrosion resistance through stable patina formation (ASTM A588/A588M).

Moderate Copper as a Binder Phase: Applied in sintered or Cu-infiltrated ferrous composites, where molten copper penetrates the iron matrix via capillary action, the same principle underlying our model (Li et al. 2024; Jang et al. 2024).

High Copper Matrix: Found in copper-rich alloys such as C19400 (ASTM B465), combining electrical/thermal conductivity with moderate strength.

4.3.1. Comparison with Alternative Alloys in Construction and Structural Applications

Versus Carbon Steel: Fe-Cu composites provide superior long-term corrosion resistance due to copper's noble potential (+0.34 V) and the formation of a stable patina.

Versus Stainless Steel (Cr-Ni): Stainless steels offer higher performance in aggressive conditions but require alloying elements (Cr, Ni) and modern production methods that were unavailable in antiquity.

Versus Bronze (Cu-Sn): The Qur'anic model prioritizes the high compressive strength and availability of iron blocks (*zubar al-ḥadīd*), using copper only as an intermediary binder. This is more resource-efficient than constructing the entire barrier from bronze, which would require vastly greater quantities of copper and tin.

In modern engineering, the principle of liquid-phase infiltration and capillary bonding is widely employed in brazing and sintered components (Way et al. 2020). This confirms that the ancient technique described in the Qur'an relies on universal physical phenomena, wetting, capillarity, and interfacial diffusion, without requiring homogeneous alloying or anachronistic technology.

5. Conclusion

This study has demonstrated that interpreting the Dhū al-Qarnayn barrier as a homogeneous metallurgical alloy poses significant scientific and historical challenges. The inherent immiscibility of the Fe-Cu system, as evidenced by the Springer Materials (n.d.) database, and the thermal ceiling of 6th-century BCE bloomery technology (Tylecote 1992), render bulk alloying or large-scale fusion welding an engineering impossibility for that era. These technical deadlocks suggest that the Alloy Hypothesis may be a result of applying modern metallurgical concepts to an ancient narrative.

In contrast, the proposed Composite Engineering Model offers a solution that is both scientifically sound and historically plausible. By shifting the focus from atomic-level alloying to interfacial thermal bonding, this model aligns seamlessly with the sequential steps described in the Qur'anic text. The process of pouring molten copper over pre-heated iron blocks acts as a sophisticated system of capillary infiltration (brazing). This method allowed ancient engineers to: achieve structural unification (*radm*) without the need to melt the massive iron core; provide a permanent electrochemical shield against corrosion, utilizing copper's noble reduction potential (+0.34 V); and create an impenetrable, voidless barrier resistant to mechanical leverage.

Ultimately, the strength of this model lies in its adherence to the natural laws of physics and metallurgy. It reveals that the construction of the barrier did not require a departure from the physical realities of the ancient world; rather, it was a masterpiece of composite design. By using copper not as an alloying element, but as a structural and chemical intermediary, the project achieved a level of durability and integrity that remains a testament to advanced ancient engineering, realized through a deep understanding of the materials at hand.

Acknowledgements

The author extends sincere thanks to the Research Affairs of Shahid Beheshti University for their support. Special gratitude is also due to Seyyed Mohammad Hossein Alavi Nejad (Shahid Beheshti University) for his valuable suggestions and insightful feedback.

Declarations

Funding: No funding was received for conducting this study.
Conflict of Interest: The author declares no competing interests.

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