A Comparative Study of Ancient Leather Processing Technology Based on Excavated Documents and Physical Artifacts: A Case Study of the Warring States Period to the Han Dynasty

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ABSTRACT Understanding the relationship between material processing, microstructural evolution, and functional performance is a fundamental issue in modern engineering materials research and provides useful perspectives for the design of advanced fibrous and dielectric materials. Against this background, this study investigates ancient Chinese leather technology through a comparative analysis of excavated technical documents and archaeological artifacts from the Warring States to the Han Dynasty. Focusing on the manufacturing pathway from raw hide to finished products, the study examines the chemical and mechanical treatments applied to stabilize collagen fiber networks and compares the standardized procedures recorded in the Kaogongji with the actual characteristics observed in excavated leather artifacts. Using the well-preserved Yanghai lamellar armor as a representative case, the analysis demonstrates that practical workshop production frequently adopted minimally processed rawhide rather than thoroughly tanned leather in order to maximize hardness and penetration resistance for military applications. The results reveal that ancient artisans deliberately adjusted processing routes according to functional requirements, establishing optimized structure –property relationships instead of rigidly following standardized prescriptions. Furthermore, the combination of rawhide substrates with lacquer coatings illustrates an early multi-material engineering strategy for balancing mechanical strength and environmental durability. This study not only provides new archaeological evidence for understanding ancient leather manufacturing but also offers valuable insights into process optimization and performance-oriented design principles for fibrous materials and composite engineering systems.

INDEX TERMS tanning technology, natural fibrous material, material characterization, archaeological leather, kaogongji

I. INTRODUCTION

THE Warring States Period (475-221 BCE) and the succeeding Han Dynasty (202 BCE-220 CE) constitute a foundational epoch in Chinese history, marked by incessant warfare, political consolidation, and unprecedented technological innovation. The demands of this era, particularly the rise of large, infantry-based armies and the logistical needs of sprawling empires, catalyzed advancements across numerous craft industries[1]. Among the most vital of these was the production of leather. As a material, leather offered a unique combination of strength, flexibility, and relative lightness, making it indispensable for the machinery of war and the functions of the state[2,3]. Its production, from a raw animal hide to a precisely engineered final product, encompassed a complex technological system that reveals much about the material science, economy, and social organization of the time[3,4].

The significance of leather in ancient China extended far beyond a single application. In the military sphere, it was the primary material for the lamellar armor (jia 甲) that protected soldiers, the shields (dun 盾) used by infantry, the scabbards and grips of swords, and the quivers that held arrows[1,5]. It formed the critical connecting components of chariots—reins, traces, and harnesses—which remained symbols of power and key elements of command even as cavalry gained prominence[6]. Beyond the battlefield, leather was fashioned into boots and belts, drumheads for ritual and communication, water skins for soldiers and

travelers, and durable containers[7]. The ubiquity of this material underscores the importance of the technologies developed to process and preserve it. The transformation of a perishable hide into a stable, functional object was a cornerstone of ancient manufacturing, demanding sophisticated knowledge of both mechanical and chemical processes[8].

Our understanding of these ancient technologies is drawn from two principal, and often conflicting, categories of evidence. The first is textual: prescriptive documents that outline the proper methods of craft. The foremost among these is the Kaogongji (《考工記》, The Record of Trades), a unique section of the Rites of Zhou (《周禮》). Likely compiled in the late Warring States or early Han period, the Kaogongji presents a highly rationalized and systematic vision of state-regulated craftsmanship[9]. It details the work of the weiren (韋人, leatherworker), providing recipes, timelines, and quality benchmarks for processing hides. These texts, however, represent a normative framework likely intended for a specific context, such as state-sponsored ritual or elite workshops, rather than a universal manual for all production. This framework prized qualities like longevity, symbolic value, and meticulous finishing appropriate for goods serving the court and state. They articulate how leather should be made, particularly within the context of elite workshops serving the court and the state[3].

The second category of evidence is archaeological: the physical remnants of leather goods that have survived for over two millennia. Due to the organic nature of leather, its preservation is exceptionally rare, limited to sites with specific environmental conditions, such as the arid deserts of the Tarim Basin in Xinjiang or the anaerobic, waterlogged tombs of the former Chu kingdom in the Yangtze River valley[10,11]. Despite their scarcity, these artifacts—suits of armor, boots, chariot fittings, and more—provide direct, empirical data. They are the tangible outcomes of the production processes. Modern scientific analysis, including scanning electron microscopy (SEM), proteomics, and multispectral imaging, allows for an unprecedented level of material characterization[12,13]. W Modern analytical methods allow researchers to identify the animal species used, analyze the microstructure of the collagen fibers, and infer the methods of processing, offering a crucial dataset to test the claims of the ancient texts.

This paper undertakes a focused comparative study, bridging the epistemological gap between the prescriptive texts and the physical artifacts. While referencing the broader spectrum of leather goods, it will concentrate on leather armor as its primary case study, as armor is both prominently discussed in the Kaogongji and constitutes the most complex and well-preserved category of leather artifact from the period. It is important to note that the most complete surviving example of such armor, discovered at the Yanghai cemetery, predates the Warring States period and the compilation of the Kaogongji. However, its exceptional preservation provides an invaluable and unparalleled technological baseline. This earlier artifact allows us to establish a material tradition of leatherworking against which the later, idealized prescriptions of the Kaogongji can be critically evaluated, illuminating potential continuities and shifts in technological paradigms over time. This research addresses a central question: To what extent did the actual practice of leatherworking, as revealed by archaeological science, conform to the sophisticated and codified standards described in contemporary technical literature? This study hypothesizes that the divergence between textual ideals and physical artifacts will be most pronounced in mass-produced items like military armor, where pragmatic concerns of material availability and functional optimization superseded idealized processes. By juxtaposing these two distinct lines of evidence, this research aims to construct a more nuanced and accurate understanding of ancient leather technology, exploring the complex interplay between state-sponsored theory and the material realities of workshop practice in early imperial China.

II. TEXTUAL EVIDENCE FROM THE KAOGONGJI

The Kaogongji is an unparalleled document in the study of ancient technology, not only in China but globally. Unlike simple inventories or descriptions, it attempts to articulate the underlying principles and standardized processes of various crafts, from metallurgy to chariot construction[14]. Its section dedicated to the weiren provides a detailed, if laconic, account of a rationalized system for leather production. The core philosophy of this system is that the processing of a hide must be precisely tailored to its intended function, a principle that demanded a deep, empirical understanding of material properties[14]. The text is prescriptive, using formulaic language to outline steps, proportions, and timelines, reflecting a bureaucratic desire to control and replicate quality across state-run workshops.

The treatise begins by categorizing hides based on their source and intended use. It makes a clear distinction between the thick, tough hides of animals like rhinoceros (xi 犀) and buffalo, designated for the highest grades of armor (jia 甲), and the more pliable skins of deer or other animals, suitable for drumheads or soft leather goods[15]. For example, it states that rhinoceros hide is the premier material for armor, a claim that sets a high standard for material selection. This initial step of classification is critical, as all subsequent processing stages are dependent on the intrinsic properties of the chosen raw material. The text specifies different soaking and curing times for hides of different thicknesses, demonstrating an awareness of how processing must be adapted to the materials structure.

The central technological process described is the transformation of raw hide into stable leather, a procedure involving de-hairing, fleshing, and tanning. The Kaogongji details a labor-intensive method of soaking and manipulating the hides. It describes a cycle of immersion and drying, combined with mechanical working (stretching and softening), which was essential for preparing the collagen

fiber network to receive tanning agents. While the text does not use modern chemical terminology, its descriptions strongly imply a form of vegetable tanning, which utilizes the tannins found in bark, wood, and other plant matter to cross-link and stabilize the collagen proteins, rendering the hide imputrescible. The emphasis on prolonged treatment—sometimes suggesting cycles lasting for months—points to a process designed for thorough, deep penetration of tannins, which would result in a durable, flexible, and long-lasting leather.

Furthermore, the Kaogongji establishes a sophisticated system of quality control based on sensory evaluation. The finished product was not judged by a single metric but by a range of qualities appropriate to its function. For drum leather, the text states the hide must be tanned until it is thin and resonant, producing a clear, carrying sound when struck. For armor, the implicit qualities are toughness and resistance to penetration. For other items, suppleness and uniform texture were key. The text uses phrases like seasoning it to its essence to describe the successful completion of the process, indicating that the artisan was expected to develop a connoisseurs feel for the material, understanding when the desired transformation was complete. This qualitative assessment, combined with the quantitative recipes, paints a picture of a craft that was both a science and an art. However, it is crucial to recognize the nature of this document. The Kaogongji was not a common artisans workbench manual; it was an idealized compilation, likely representing the best practices of the states premier workshops. Its purpose was as much political as it was technical: to demonstrate the order and wisdom of the state in regulating production and ensuring the quality of essential goods, especially those for ritual and military use.

III. ARCHAEOLOGICAL EVIDENCE: THE MATERIAL REALITY

The archaeological record for leather from the Warring States and Han periods provides a crucial, albeit fragmentary, material counterpoint to the idealized processes of the Kaogongji. Survival of these organic artifacts is rare, but finds from key sites offer invaluable physical data on the materials, construction, and performance of ancient leather goods[16]. The most significant and well-studied examples are suits of lamellar armor, which, due to their composite nature and high-status association, were sometimes preserved with remarkable integrity.

The most illuminating case study to date is the suit of armor discovered in a tomb at the Yanghai cemetery near Turfan, Xinjiang, radiocarbon dated to 786–543 BCE[13]. While this date places the armor squarely in the Spring and Autumn Period, preceding the era central to this study, its near-perfect condition offers a rare window into the principles of armor construction that informed subsequent periods. It serves as a crucial material precedent, demonstrating a sophisticated technological choice for hardness and protection that likely persisted and contrasts sharply with the later, state-codified ideals found in the Kaogongji. This nearly complete suit, composed of over 5,400 individual scales laced together, provides an unprecedented window into ancient military technology. Scientific analysis published in Quaternary International revealed several crucial details that stand in stark contrast to the Kaogongjis prescriptions. Firstly, material analysis (proteomics) determined that the scales were fabricated from cowhide, not the prized rhinoceros hide mentioned in the text[13]. This indicates a pragmatic choice based on the abundant availability of cattle as a domestic resource, rather than the rare and exotic rhinoceros. Secondly, the microstructural analysis from this study showed that they were not fully tanned leather but were instead made of rawhide. The collagen fibers lacked the characteristic stabilization of a thorough tanning process. This was likely a deliberate technological choice: rawhide, when dried under tension, becomes extremely hard and stiff, offering excellent resistance to puncture and slashing. A full vegetable tan, as implied by the Kaogongji, would have produced a more flexible but softer material, less suitable for rigid armor plates. The Yanghai armor thus represents a different technological paradigm, one that prioritized hardness over the durability and flexibility that come from tanning. Finds from other regions corroborate this picture of technological diversity. In the waterlogged tombs of the former Chu state, such as the famous tomb of Marquis Yi of Zeng (c. 433 BCE), remnants of lacquered leather armor have been found[11]. While the leather itself is often severely degraded, its combination with lacquer is significant. A thick coating of lacquer would have served multiple purposes: it provided a hard, glossy exterior, offered substantial protection against moisture (the primary weakness of rawhide), and helped to bind the leather scales together. This leather-lacquer composite represents a sophisticated material engineering solution, combining the tensile strength of the fibrous leather substrate with the compressive strength and water resistance of the lacquer coating—a practical innovation not detailed in the tanning sections of the Kaogongji. This finding directly reinforces the studys central thesis. It demonstrates that artisans were not merely following a single prescribed tanning method but were actively creating multi-material composites to solve specific engineering challenges—in this case, mitigating the primary weakness of rawhide or minimally processed leather (vulnerability to moisture). This focus on functional performance through material synergy represents a clear deviation from the single-material, idealized process described in the texts. Further evidence for armor comes from the Qin Dynasty Terracotta Army, where the unarmored appearance of many warrior figures is now believed to be misleading. Detailed analysis of paint traces and surface impressions on the statues suggests they originally wore armor constructed from small leather plates, which decayed long ago, leaving only their ghostly imprints.

Beyond armor, other leather artifacts demonstrate a wider

range of processing techniques. At the Han Dynasty site of Niya, a key oasis on the Silk Road, well-preserved leather boots have been unearthed. These items, designed for flexibility and comfort, appear to have been made from a more thoroughly processed, pliable leather, suggesting that the time-consuming tanning methods described in the texts were indeed employed for products where suppleness was a primary requirement. Crucially, this does not contradict the evidence from armor but rather strengthens the argument for function-specific processing. It indicates that the knowledge of thorough tanning as described in the Kaogongji existed, but its application was judiciously reserved for items where flexibility was the desired primary property. This selective application of different techniques for different products—rawhide for hardness in armor, tanned leather for flexibility in footwear—is the very essence of the pragmatic workshop reality that diverges from any single, universal standard. Similarly, excavations have yielded leather components of horse harnesses, quiver panels, and bags. These artifacts often show signs of careful stitching and finishing. The choice of processing technique was clearly function-specific. While military armor prioritized hardness through the use of rawhide, everyday items that required flexibility received a more complete tanning treatment. This archaeological diversity strongly suggests that ancient leatherworkers possessed a broad repertoire of techniques and applied them judiciously, making rational, resource-aware decisions based on the intended function of the final product, rather than universally adhering to a single, idealized standard.

IV. DISCUSSION

The juxtaposition of the idealized standards in the Kaogongji with the material evidence from excavated artifacts reveals a complex and nuanced relationship between prescriptive texts and workshop practice. While it must be acknowledged that the archaeological record for leather is inherently fragmentary, the pattern emerging from these diverse key sites consistently points toward pragmatic adaptation over strict textual adherence. A systematic comparison of these differences, which points toward a sophisticated and adaptive technological system where artisans made deliberate choices based on a range of interacting factors, including material availability, functional requirements, economic constraints, and regional traditions. The divergence between text and object is not a sign of technological deficiency, but rather an indicator of the pragmatism and ingenuity of ancient craftspeople.

The divergence in raw material—common cowhide used for the Yanghai armor versus the prized rhinoceros hide advocated by the Kaogongji—invites a more complex interpretation than simple pragmatic adaptation. While a rational economic and logistical choice for mass production is one factor, two other possibilities, stemming from the chronological and cultural context, are crucial.

First, given that the Yanghai armor predates the compilation of the Kaogongji by centuries, it is highly plausible that the textual ideal of using rhinoceros hide was not yet established when the armor was made. The use of cowhide would therefore not be a substitution for a later standard, but a reflection of its own eras material culture. Second, as the armors Assyrian-style design suggests, it may represent a distinct, non-Sinitic technological tradition altogether. In this context, cowhide could have been the standard, preferred material, making its use a direct expression of a different cultural practice, rather than a deviation from a Chinese one.

The most significant technological divergence is found in the tanning process itself. The Kaogongjis description of a lengthy, thorough tanning process to produce durable, flexible leather contrasts sharply with the use of hard rawhide for the Yanghai armor. This cannot be seen as an oversight. It was a calculated decision based on a sophisticated understanding of structure-property relationships. The technological choice between rawhide and tanned leather is fundamentally a choice in how to manipulate the collagen fiber network at a microscopic level. The production of rawhide is a physical process that involves more than simple drying; it requires dehairing, fleshing, and critically, stretching the hide under tension as it loses water. This tension pulls the collagen fibers into a dense, tightly packed, and interlocked matrix, which becomes rigid and horn-like as strong hydrogen bonds form between the fibers upon drying. The result is a natural composite material that excels in hardness and resistance to penetration. In contrast, vegetable tanning is a chemical transformation. Large polyphenol molecules (tannins) from plant matter infiltrate the collagen structure and form stable, permanent cross-links between the individual fibers. This chemical bonding prevents the fibers from gluing together when dried and protects them from bacterial decay, creating a stabilized material that remains permanently flexible, durable, and more resistant to water. For armor lamellae, the paramount mechanical property was hardness (resistance to deformation) and penetration resistance. Rawhide, when de-haired, defleshed, and dried under tension, produces a material with a densely packed collagen fiber structure that is exceptionally hard. The full chemical stabilization offered by tanning, while making the material resistant to rot and more flexible, would have softened it, thereby compromising its primary protective function. The artisans made a calculated trade-off: they sacrificed the superior water resistance, resistance to decay, and longevity afforded by the high-labor, time-consuming tanning process for the superior protective hardness and faster production time of rawhide.The subsequent application of lacquer, as seen in Chu artifacts, was a brilliant secondary innovation designed to mitigate the main drawback of rawhide—its vulnerability to moisture. This multi-material, composite solution demonstrates a deep, practical knowledge of materials engineering that is more complex than the single-process ideal of the Kaogongji.

These discrepancies suggest a re-evaluation of the Kaogongjis purpose. Instead of viewing its prescriptions as an

idealized version of workshop reality, it is more productively interpreted as a rational standard for an entirely different production context. The thorough tanning and use of premium materials it describes were likely the real, practical standards for goods intended for ritual, ceremonial, or high-elite use, where durability, flexibility, and symbolic value were the primary functional goals. Therefore, the rawhide armor seen in the archaeological record is not a pragmatic failure to meet this standard, but rather evidence of a parallel and equally valid technological system optimized for a different set of requirements: the rapid, cost-effective mass production of military equipment where hardness and penetration resistance were the paramount virtues. The actual practice of leatherworking across the vast territories of the Warring States and the Han empire was likely far more diverse. Knowledge was primarily transmitted through apprenticeship and oral tradition within workshops, leading to the development of regional styles and techniques adapted to local resources and needs. The Assyrian-style design of the Yanghai armor, for instance, points to technological exchange with Central Asian cultures along the routes that would become the Silk Road, an influence entirely outside the world described by the Kaogongji. This further underscores the value of examining this earlier artifact; it reveals that the technological repertoire available to Warring States and Han artisans was not a closed system, but was built upon a long history of both indigenous development and external influences that predated the Kaogongjis compilation. The practices seen in the Yanghai armor represent a deep-rooted, pragmatic tradition that the later, idealized state standards sought to rationalize, but could not fully supplant. Therefore, the archaeological record is not just a corrupted version of the text; it is evidence of a multitude of parallel, thriving technological traditions.

V. CONCLUSION

This comparative study of ancient Chinese leather processing from the Warring States to the Han Dynasty reveals a significant and meaningful divergence between the idealized technological prescriptions of the Kaogongji and the tangible evidence of archaeological artifacts. The textual sources present a highly rationalized, systematic, and standardized f ramework for production, reflecting the states ambition to control and perfect the manufacture of essential goods. This framework emphasized careful material selection, lengthy and thorough tanning processes, and meticulous quality control to create superior, durable leather suited for elite and ritual functions.

In contrast, the archaeological record, though limited by the challenges of organic preservation, consistently paints a picture of greater pragmatism, adaptation, and technological diversity across the examined artifacts. The choices made by ancient artisans—such as the use of readily available cowhide instead of rare rhinoceros hide and the preference for hard rawhide over flexible tanned leather for armor—were not failures to meet an ideal standard. Instead, they were deliberate, intelligent engineering decisions. These choices were driven by a sophisticated, practical understanding of structure-property relationships, where materials and processes were optimized for specific functional requirements, such as maximizing hardness for armor, within the real-world constraints of material availability and the economic demands of mass production. The development of leather-lacquer composites further highlights a tradition of practical innovation that existed alongside, and often independent of, the codified textual ideals.

Ultimately, this research demonstrates that the Kaogongji and the archaeological record must be read in concert to achieve a holistic understanding of ancient technology. The text provides the theoretical and ideological framework, the ought, while the artifacts provide the material reality, the is. Their synthesis reveals that ancient Chinese leatherworking was not a monolithic practice, but comprised multiple, parallel technological traditions, each rationally optimized for different functional contexts—from the ritual and elite standards codified in texts to the mass-production realities reflected in military artifacts. It was a system where state-sponsored standards coexisted with a rich tapestry of regional and workshop-based traditions, all shaped by the constant negotiation between idealized goals and the practical challenges of making things. This study not only illuminates the specific history of leather technology but also offers a methodological model for investigating any ancient craft, urging a critical approach that values both the prescriptive text and the physical object as equally important, though fundamentally different, witnesses to the technological ingenuity of the past. Future research, leveraging advancing analytical techniques on a wider array of artifacts, promises to further unravel the complexities of this essential ancient industry.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

Bo Wang designed the study; all authors conducted the study; Bo Wang and Yin Zhou collected and analyzed the data. Bo Wang and Yin Zhou participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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