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ORIGINAL REPORT



Enhancing strength and ductility in heterolamellar medium-Mn steel through bamboo-like microstructure design

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ABSTRACT

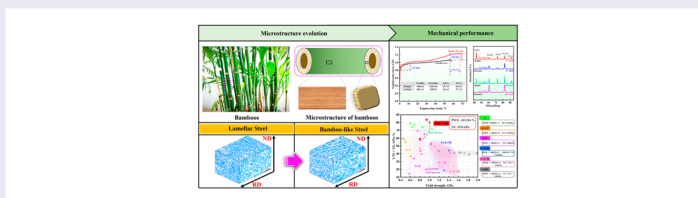
Nature has long inspired technological innovations, fostering the rapidly developing field of bionics. Inspired by the microstructure of bamboo, we have developed a bamboo-like structure for steel. This novel steel achieves a tensile strength exceeding 1200 MPa and a uniform elongation nearing 68%, resulting in a product of strength and uniform elongation up to 83 GPa·%. The high strength of the steel is primarily attributed to its ultra-fine lamellar grains. Additionally, the graded occurrence of multiple deformation mechanisms collectively maintains its exceptional work-hardening capability. This study presents a new approach to enhancing the performance of medium-Mn steels.

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KEYWORDS

Heterolamellar microstructure; bamboo-like steel; medium-Mn steel; strength–ductility synergy; ferrite + austenite



Impact Statement

A bamboo-like steel consisting of lamellar ferrite and austenite alternating along the rolling direction, providing a new path to produce medium-Mn steels with outstanding mechanical properties.

1. Introduction

The advancement of modern industrial technology, encompassing construction engineering, transportation, and national defense, necessitates metal components with enhanced strength and ductility [1]. However, achieving simultaneous improvements in the two properties has been a significant challenge due to their inherent trade-off [2,3]. Therefore, the development of advanced metal materials with high strength and ductility holds paramount scientific and engineering importance.

In recent years, researchers exploring natural biomaterials such as bones, shells, and bamboo have noted their evolution over millions of years to achieve an optimal integration of structural and mechanical properties [4,5]. These materials have effectively utilized the inherent incompatibilities of microstructures, thereby

resolving the trade-off between strength and ductility [6–10]. This is why they have been selected by natural evolution and are frequently investigated by mankind. Shi *et al.* [11] designed a 'biomimetic fishbone' microstructure for hierarchical multiscale crack buffering, achieving an ultra-high uniform elongation ($\sim 50\%$) without compromising strength. Zhang *et al.* [12], inspired by abalone and mantis shrimp shells, mimicked these structures in metallic systems, yielding significant enhancements in strength and toughness with 2–8 times increase in fracture energy over conventional composites. Motomichi Koyama *et al.* [13] were inspired by the superior fracture toughness of bones and designed a biomimetic steel with characteristics of multiphase, metastable, and lamellar structures. This steel exhibited outstanding resistance to fatigue fracture. Inspired by bamboo's natural structure,

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Du *et al.* [14] developed a medium-carbon steel with a bamboo-like heterogeneous structure. By coupling heterogeneous boundaries with cementite, they created a point-line topology that effectively transfers stress and reduces stress concentration. This design significantly enhances yield strength while maintaining excellent ductility. Among these biomaterials, bamboo has been an important resource for human society since ancient times, playing a crucial role in both production and daily life [15,16]. Bamboo possesses exceptional mechanical properties, including strength, plasticity, and toughness, and embodies profound principles of material design and structural mechanics [17].

Building on this natural inspiration [18,19], we have devised a biomimetic steel featuring a bamboo-like microstructure comprising alternating lamellar ferrite and austenite aligned along the rolling direction. This laminar arrangement mimics the cellulose and lignin structure found in natural bamboo, yielding a remarkable tensile strength of 1230 MPa coupled with a substantial uniform elongation of 68%. This study introduces a novel avenue to enhancing steel performance, promising widespread application in engineering structures.

2. Materials and methods

The microstructure of bamboo, composed of cellulose and lignin, is arranged in parallel and alternating patterns along its growth direction (Figure 1(a)). These microstructures confer bamboo with remarkable strength and toughness. We are inspired by this design to create similar microstructures in medium Mn steels (MMnSs). The microstructure of the growth direction of bamboo (Figure 1(a2)) corresponds to the alternating distribution of ferrite and austenite in the real microstructure of RD-ND plane (Figure 1(a22)). The cross-sectional view of bamboo (Figure 1(a3)) corresponds to the equiaxed grain distribution observed in the TD-ND plane of the steel microstructure (Figure 1(a33)). Figure 1(b1, b2) display the schematic three-dimensional (3D) microstructures of conventional MMnS and the proposed bamboo-like steel, respectively. Previous studies have shown that a lamellar microstructure consisting of martensite and ferrite can exhibit excellent mechanical properties. However, such random lamellar microstructure often experiences bending and rotation during deformation, leading to localized stress concentration and limiting further enhancement of its mechanical

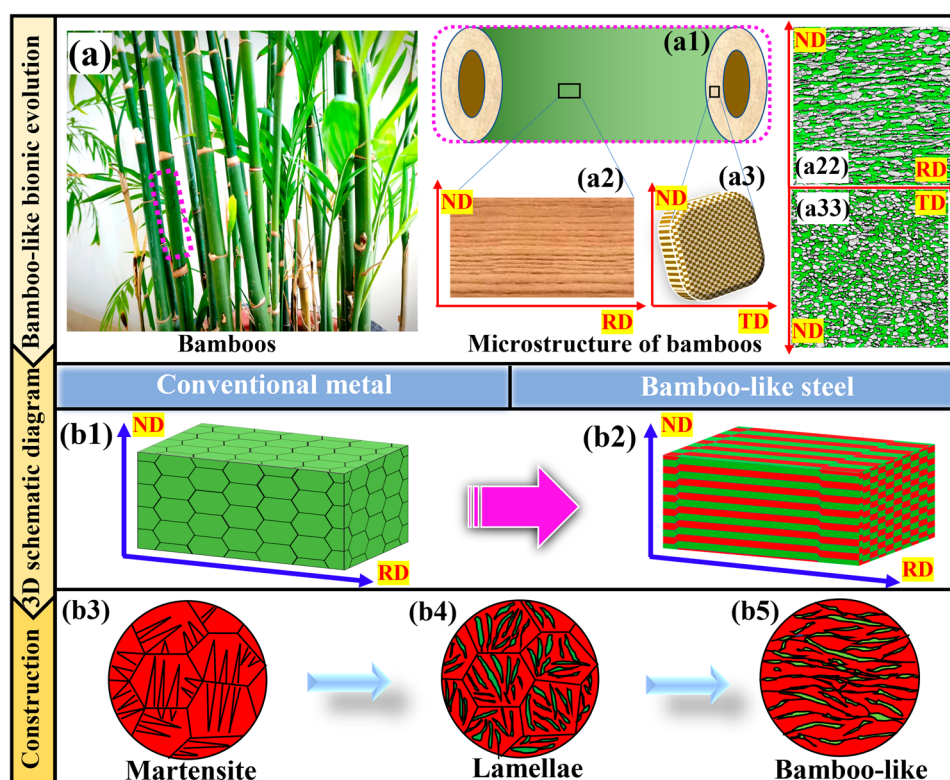


Figure 1. (a) Natural bamboo, (a1) bamboo, cross-sectional and slide view of Fig. a1(a2) Cross-section, (a3) Side view, (a22) and (a33) The EBSD BC map of the constructed bamboo-like steel overlaid with the austenite (green) phase diagram; 3D schematic diagram of conventional steel (b1) and bamboo-like steel (b2). (b3-b5) Schematic diagram of construction process of bamboo-like steel.

properties [2,20]. To address this, we start with a martensitic structure (Figure 1(b3), HR-steel, Hot Rolling) and convert it into lamellar steel (Figure 1(b4), L-steel) via intercritical annealing. Specifically, we deform the L-steel at the intercritical annealing temperature, producing bamboo-like steel (Figure 1(b5), BL-steel) with alternating layers along the rolling direction. The detailed thermomechanical treatment process (Fig. S1) is described in the supplementary file.

3. Results and discussion

The microstructures of the L- and BL-steels are shown in Figure 2 (Phase analysis is detailed in Figs. S2 and S3). L-steel exhibits a random arrangement of lamellar ferrite and austenite (Figure 2(a)), while BL-steel shows lamellae arranged alternately along the rolling direction (Figure 2(d)). TEM images indicate that the BL-steel has smaller lamellae compared to the L-steel (Figure 2(b, e)). Figure 2(c, f) depict the inverse pole figure (IPF) images of L- and BL-steels, respectively. Figure 2(g, h) depict the inverse pole figure (IPF) maps for the TD-ND planes of L- and BL-steels, respectively.

In the L-steel, the microstructure (ND-TD plane) closely resembles that of the RD-ND plane. Conversely, the IPF map of the BL-steel (ND-TD plane) exhibits features reminiscent of a bamboo cross-section, characterized by uniformly distributed equiaxed grains with an average effective grain size smaller than 1 μm . Figure 2(g, h) depict the microstructures of L- and BL-steels 3D-reconstructed from EBSD phase maps in the RD, TD, and ND. These microstructures affirm the highly successful construction of the bamboo-like steel.

The engineering stress-strain curves of BL-steel and L-steel are compared in Figure 3(a). L-steel exhibits commendable tensile properties with an ultimate tensile strength (UTS) of approximately 1050 MPa and a uniform elongation (UE) of about 56.3%. BL-steel demonstrates a yield strength (YS) of approximately 940 MPa, an UTS of around 1235 MPa, and UE of about 67.7%. Figure 3(b) shows the work hardening rate of L- and BL-steels. Both samples exhibit typical three-stage

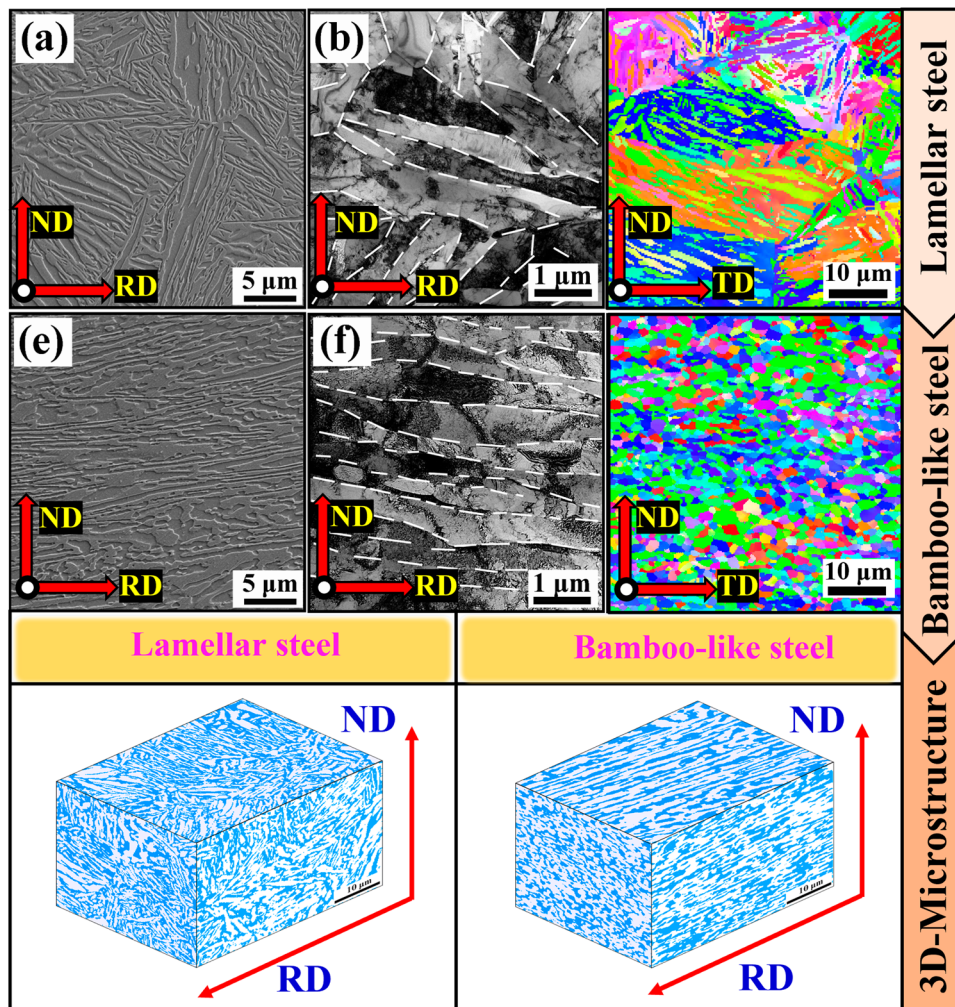


Figure 2. (a)-(c) and (d)-(f) show the SEM, TEM, and IPF images of L-steel and BL-steel; (g) and (h) represent the three-dimensional reconstructions of L-steel and BL-steel using EBSD, where white denotes ferrite and blue denotes austenite.

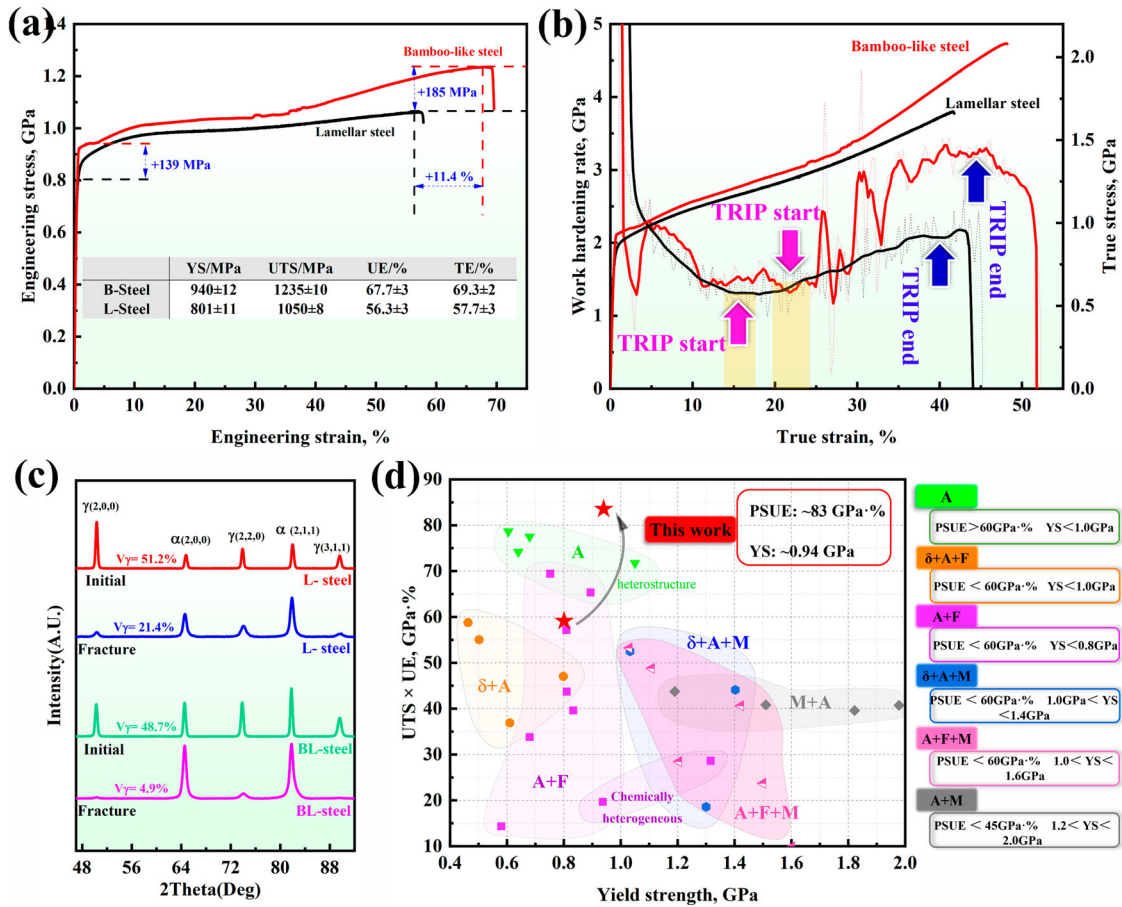


Figure 3. (a) and (b) the engineering stress-strain curves and work hardening rate curves of L- and BL-steels; (c) XRD analysis of the volume fraction of austenite before and after tensile in L- and BL-steels; (d) The UTS $\times$ UE – YS data of MMnSs reported in literature alongside the present steel (austenite [1,7,22], austenite + α -ferrite [1,23–25], δ -ferrite + austenite + α -ferrite [1,24], δ -ferrite + austenite + martensite [1,24,26], α -ferrite + austenite + martensite [1,24], and austenite + martensite [1,24,27,28]).

work hardening, marked by TRIP start (red arrow) and TRIP end (blue arrow) [21]. Initially, the work hardening rate of L-steel and BL-steel follows a similar trend. However, BL-steel shows a notable increase in work hardening rate with increasing strain. This significant enhancement in work-hardening capacity improves the strength and ductility of BL-steel [8]. Figure 3(c) indicates that the initial (fracture) austenite volume fractions in L-steel and BL-steel are 51.2% (21.4%) and 48.7% (4.9%), respectively. The conversion ratio of austenite increased from 58.2% to 89.4%. Figure 3(d) summarizes the UTS $\times$ UE – YS data of MMnSs reported in literature alongside the present steel (Red star). MMnSs are categorized into six groups based on different microstructures. Typically, the product of UTS and UE (PSUE) of MMnS reaches 60 GPa·%, mostly observed in austenitic MMnS. However, due to the limitation of Mn content, common MMnS mostly exhibits a multiphase microstructure. Among these, austenite-ferrite MMnS is the most extensively studied, with excellent achievable performance. Achieving the PSUE exceeding 60 GPa·% is extremely

challenging. Although the designed random lamellar structure of L-steel has met this benchmark, BL-steel demonstrates an excellent strength-ductility balance of 80 GPa·%. This result highlights the potential of the proposed bamboo-like structure design to effectively resolve the strength-ductility trade-off in typical MMnSs.

The substantial enhancement in the comprehensive mechanical properties of BL-steel can be mainly attributed to the bamboo-like microstructure that we have engineered. During deformation of dual-phase steel, the softer phase undergoes plastic deformation first, while the harder phase remains in elastic deformation, limiting the plastic deformation of the softer phase [2,20]. This leads to strain accumulation at the phase boundaries, a phenomenon that is particularly pronounced in lamellar steels. In lamellar steels, the alternating layers further constrain each other, resulting in increased stress accumulation at the interfaces. Simultaneously, this process triggers interface incompatibility between the two phases, leading to the development of HDI stresses [29,30]. Under the influence of these stresses, additional

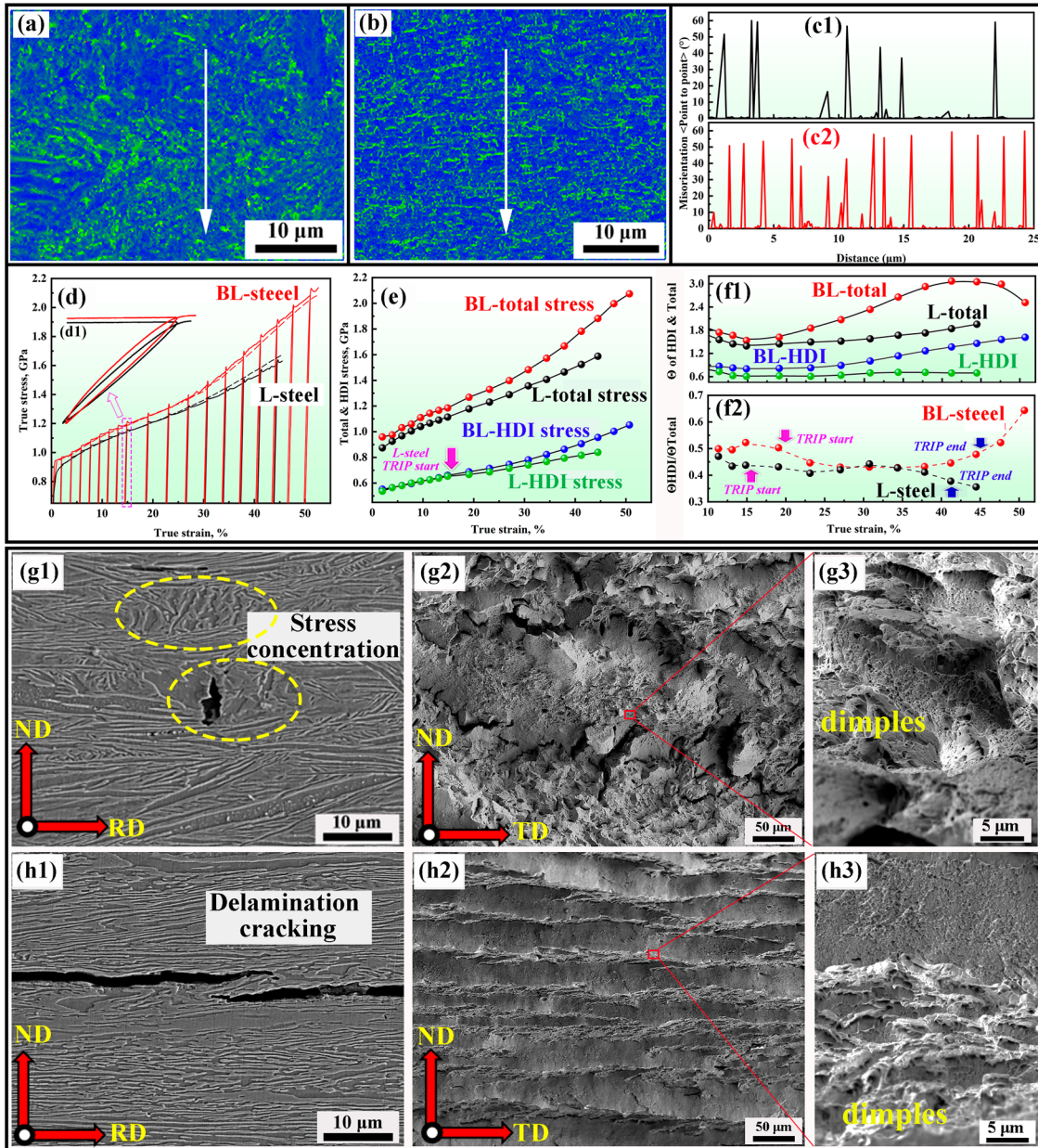


Figure 4. (a) and (b) KAM for L- and BL- steels; (c) Misorientation measured along white arrows across lamellae in L- and BL-steels. (d) True stress-strain curves of unload-reload cycle (solid lines) and uniaxial tension (dashed lines) for L- and BL- steels; (e) The Total and HDI stress of L- and BL- steels at different strains; (f1) and (f2) $\Theta_{Total} = d\sigma_{total}/d\epsilon$ and $\Theta_{HDI} = d\sigma_{HDI}/d\epsilon$; (g1) – (g3) and (h1) – (h3) The microstructure near the fracture of the ND-RD plane of L-steel and BL-steel, as well as the fracture of the ND-TD plane.

work hardening occurs, resulting in delocalized strain characteristics induced by heterogeneity [10]. This effect becomes more pronounced with denser interface distributions. Figure 4(a, b) reveal that, compared to L-steel, BL-steel demonstrates a more uniform distribution of kernel average misorientation (KAM), displaying a typical alternating distribution of strain differences along the rolling direction. Subsequent point-to-point misorientation analyses (Figure 4(c)) conducted on random regions of both steels further confirm the dense and alternating distribution of heterogeneous interfaces in BL-steel.

Both traditional L-steel and BL-steel exhibit typical heterogeneous structures. The strain hardening behavior during deformation can be analyzed through loading-unloading-reloading tensile tests. Figure 4(d) demonstrates the cyclic loading curves of the two steels overlaid with their respective uniaxial tensile curves, revealing a high degree of consistency. The hysteresis loops (Figure 4(d1)) clearly indicate a significant Bauschinger effect, allowing us to estimate the contribution of the HDI stress to the flow stress [31]. The HDI stress strengthening is evaluated by Zhu et al.'s method [10,32]. The specific

formulas are as follows : $\sigma_{HDI} = (\sigma_u + \sigma_r)/2$, where σ_r and σ_u are the reloading yield stress and the unloading yield stress, respectively. Subsequently, Figure 4(e) illustrates the total stress and HDI stress at different strain nodes. It is observed that as the strain increases, the HDI stress for both steels also increase. Moreover, after the onset of the TRIP effect in L-steel, the difference in HDI stresses between the two gradually increases (Figure 4(e) red arrow). This is primarily attributed to meticulous structural design, which fully exploits the microstructure of bamboo. Consequently, BL-steel demonstrates superior ability in managing strain mismatches between heterogeneous structures during deformation. To further understand the remarkable mechanical characteristics of BL steel, the tensile process is separated into three stages for detailed analysis (Figure 3(b)).

In stage I, where the TRIP effect is absent, both L-steel and BL-steel exhibit excellent plastic deformation capabilities. This is attributed to their lamellar heterogeneous structure, which allows better phase coordination under HDI hardening, compared to conventional bulk structures. Figure 4(f) shows that, prior to the onset of the TRIP effect, the main source of work hardening for L- and BL-steels is HDI hardening, with values of 0.4-0.45 and 0.5-0.55 (Figure 4(f2)), respectively. However, L-steel contains more lamellae oriented at large angles or even perpendicular to the tensile direction, resulting in severe strain mismatches in these regions (Figure 4(g1)). This leads to localized stress concentrations that prematurely trigger the TRIP effect. Figure 3(b) shows that the TRIP effect in L-steel starts at 14-17% strain, whereas in BL-steel, it starts at 20-24% strain.

In stage II, the TRIP effect is significantly enhanced, and the contribution of HDI to work hardening decreases, which is particularly evident in BL-steel (Figure 4(f2)). This suggests that the bamboo-like structure provides superior TRIP strengthening during deformation. Due to high stress concentrations in the vertical lamellar regions of L-steel during this stage, these areas become primary sites for crack nucleation, leading to premature failure before significant austenite transformation occurs (Figure 3(b) and Figure 4(g1)). Conversely, the BL-steel coordinates deformation more effectively, with stress concentrations mainly at the lamellar interfaces. This stepwise deformation enhances austenite's mechanical stability and improves stress transfer. This structure emulates bamboo's deformation process, allowing austenite in BL-steel to provide sustained and stable TRIP strengthening until nearly all austenite is consumed, marking the end of the second stage (Figure 3(c)).

In the final stage, In L-steel, severe stress localization occurs, and HDI hardening gradually weakens, leading to rapid failure. In contrast, BL-steel shows a significant

increase in HDI hardening after the TRIP effect, rising from 0.5 to 0.65 (Figure 4(f2)). This increase is due to the coordinated deformation of the alternating lamellar structure, similar to the first stage. At this point, the denser lamellar structure of martensite and ferrite facilitates better coordinated deformation of the heterogeneous structure. This unique structure and deformation characteristics enable BL steel to release stress concentration more effectively during the later stages of deformation, enhancing ductility (Figure 4(h1)). Additionally, due to the unique deformation mechanism of the lamellar structure, stress concentration primarily occurs along the phase interfaces. In the later stages of deformation, stress concentration is released through delamination cracking [33]. This type of delamination crack, aligned parallel to the tensile direction, effectively delays the failure time of the sample. Fractographic analysis shows that L steel exhibits cracks propagating in various directions, and typical dimple distribution is observed upon magnification (Figure 4(g2, g3)). In contrast, BL steel shows neatly arranged, densely distributed delamination bands with clear dimples and thinner bands upon magnification, indicative of delamination cracking (Figure 4(h2, h3)). Thus, this bamboo-like structure significantly enhances both strength and ductility compared to traditional heterogeneous lamellar structures through its unique strengthening and plasticizing mechanisms.

To more intuitively illustrate the exceptional mechanical properties of BL-steel, we have created a corresponding schematic diagram (Figure 5(a)) based on the aforementioned discussion and in-situ SEM observations (Figure 5(b-e)). Figure 5(b) shows a macroscopic image of BL-steel after fracture, where no significant necking is observed. This indicates that strain was uniformly distributed throughout the deformation process, reflecting the material's high comprehensive mechanical performance [34]. Additionally, SEM images of selected areas before and after fracture are presented in Figure 5(c, d). It can be observed that, post-fracture, the lamellar ferrite and martensite exhibited severe distortion. The distance between two typical locations increased from 3.9 μm to 6.3 μm , roughly calculating the uniform strain to be 62%.

In the stages I to II shown in Figure 5(a), the initial deformation of BL-steel demonstrates the coordinated deformation of lamellar ferrite and lamellar austenite, exhibiting the typical deformation characteristics of a heterogeneous lamellar structure. The austenite and ferrite mutually constrain each other, with strain transferring between the lamellar structures. This interaction, enhanced by HDI hardening, results in a more uniform strain distribution during deformation, thereby suppressing the premature onset of the TRIP effect. Corresponding to Figure 5(e1-e3), even at an engineering strain

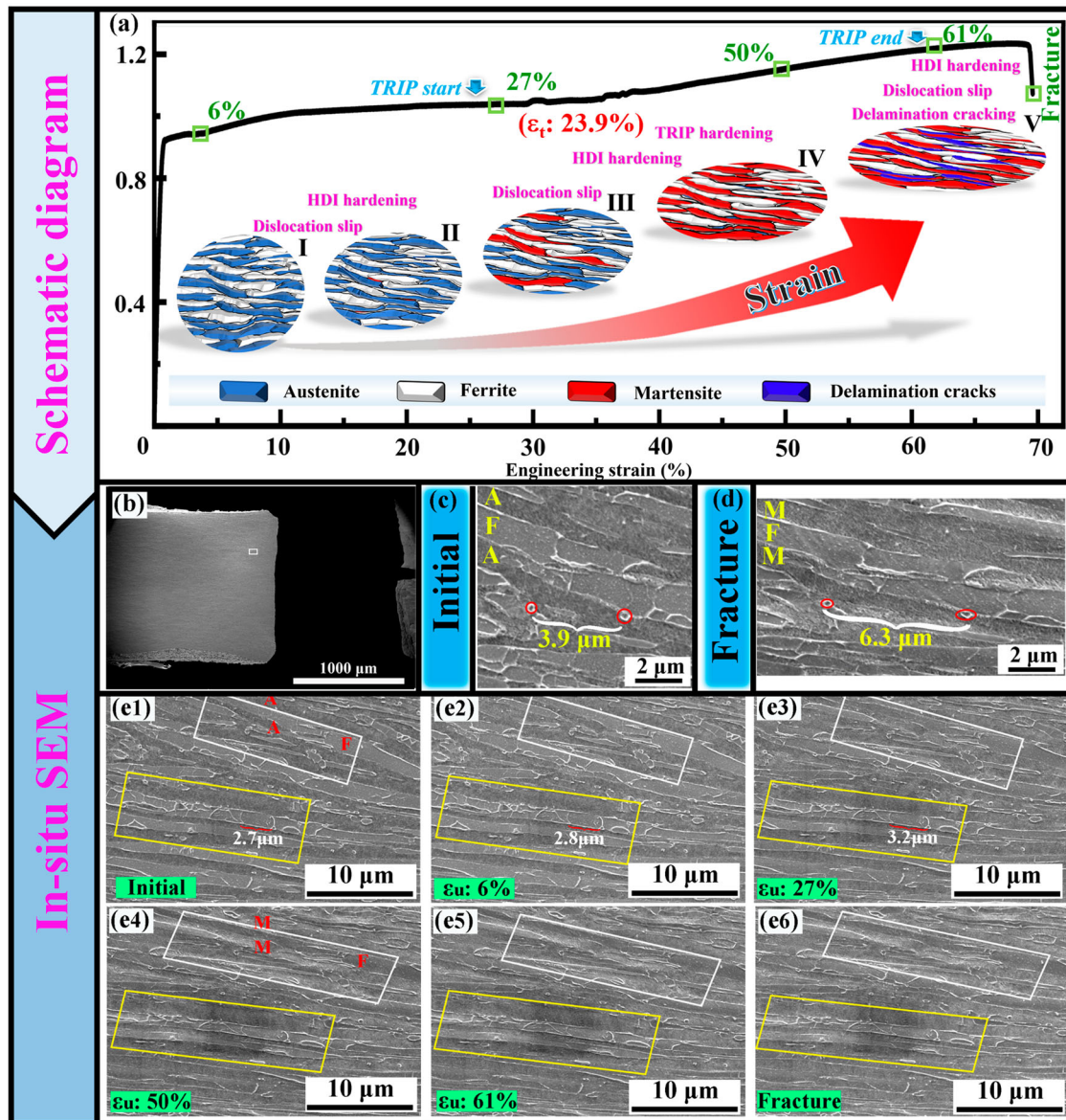


Figure 5. (a) Schematic diagrams of microstructural evolution at different deformation stages; In-situ tensile SEM images of BL-steel: (b) Macroscopic morphology of fractured sample; (c) and (d) Comparison of initial and post-fracture microstructure in selected observation areas; (e1) to (e6) Microstructural evolution observed under selected strain conditions during in-situ tensile testing.

level as high as 27% (true strain, $\epsilon_t = 23.9\%$), no significant TRIP features (martensite, white rectangles) are observed. Additionally, the typical lamellar structure is elongate and thin, as indicated by the increase in ferrite length from 2.7 μm in the initial sample to 3.2 μm at 27% strain (yellow rectangle). As the strain further increases, distinct TRIP effects emerge in stages III and IV of Figure 5(a). At this point, in addition to HDI hardening, TRIP hardening gradually becomes dominant. The deformation of the heterogeneous lamellar structure allows the entire TRIP process to proceed continuously and stably (Figure 3(c-e)) [35]. Thus, during this stage, the combined effect of both hardening mechanisms enables the material to maintain superior mechanical properties at

strains exceeding 30%. In the in-situ SEM observations shown in Figure 5(e3-e5), when entering the TRIP stage, typical martensitic structures begin to appear (Figure 5(e4), red). During the continued TRIP process, the lamellar structure still exhibits characteristics of elongation and thinning. The white and yellow rectangles clearly demonstrate these deformation features.

In the late stages of deformation (After stage V in Figure 5(a)), austenite almost completely transforms into martensite, with high strain concentrations primarily distributed at the interfaces. Interface cracking not only effectively releases this stress concentration but also, compared to the microstructure of the initial ferrite and austenite, the newly formed finer lamellar martensite

and ferrite are more capable of inducing HDI hardening. Therefore, even at high strains in the late stages of deformation, the material can still maintain a strain of 10% due to the synergistic effects of delamination and HDI hardening. Therefore, BL-steel achieves an exceptionally superior strength-ductility balance through the synergistic action of graded multiple deformation mechanisms. This performance represents a significant advance among advanced high-strength steels.

4. Conclusion

In summary, we have successfully integrated the longitudinally alternating structure found in natural bamboo into medium manganese steel using a biomimetic approach, resulting in a biomimetic steel with a bamboo-like lamellar structure. This novel material exhibits an exceptional combination of tensile strength and uniform elongation, PSUE surpassing 80 GPa·%, alongside a straightforward and easily implementable manufacturing process. This research opens up new avenues for the design of metallic materials with outstanding mechanical properties.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

Data available on request from the authors.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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