Journal of Materials, Processing and Design (2026)
Clausius Scientific Press, Canada
DOI: 10.23977/jmpd.2026.100113
ISSN 2516-0923 Vol. 10 Num. 1

Microstructural Strengthening-Toughening Mechanisms and Multi-application Development of Modern Titanium Alloys

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Keywords: Titanium alloy; Microstructure regulation; Strengthening and toughening mechanism; Additive manufacturing; Metastable engineering; Microtexture

Abstract: Titanium alloys boast low density, high specific strength, excellent corrosion resistance and favorable biocompatibility, occupying a strategic position in aerospace, deep-sea equipment, biomedical engineering and new energy sectors, and thus are highly favored by designers and researchers worldwide. Nevertheless, three long-standing bottlenecks have restricted the advancement of titanium alloys for decades: the trade-off between strength and ductility, poor machinability, and susceptibility to extreme service environments. Over the past five years, researchers have made breakthroughs addressing these challenges via metastable microstructure engineering, additive manufacturing, microtexture orientation modulation, intelligent heat treatment and other technical approaches. From the two core perspectives of microstructure regulation and strengthening-toughening mechanisms, this paper elaborates on key scientific issues including heterogeneous laminated structure design, interstitial solid-solution strengthening, phase transformation and nanocrystallization under dynamic loading, as well as room-temperature impact toughness control. Combined with experimental data from published literatures, it further clarifies the physical essence of the microstructure-property relationship. Finally, this work prospects future development opportunities and research directions for titanium alloys, offering references for follow-up research in this field.

1. Introduction

Titanium and titanium alloys serve as pivotal structural metals for the manufacturing of major equipment in national defense, deep-sea exploration and aerospace industries, owing to their high specific strength, outstanding high-temperature resistance and superior erosion resistance against seawater[1]. The core microstructural characteristics of titanium alloys are mainly determined by their allotropic transformation, namely the α↔β phase transition occurring at 882 °C. Industrially, titanium alloys are commonly classified into α-type, β-type and α+β dual-phase titanium alloys according to their microstructural constituents at room temperature. Among them, dual-phase alloys represented by Ti-6Al-4V dominate the vast majority of the titanium alloy market due to their balanced comprehensive mechanical properties[2].

Nevertheless, with the ever-growing demand for lightweight design and ultimate load-bearing capacity from high-end equipment such as aero-engines, deep submersibles and hypersonic vehicles, conventional titanium alloys exhibit prominent deficiencies in three major aspects.

Firstly, there exists a strength-ductility trade-off. When the yield strength is raised above 1200 MPa, the uniform elongation usually drops sharply to less than 5%, which severely restricts the further application of titanium alloys[3]. Conventional equiaxed microstructures feature favorable ductility yet insufficient strength, while lamellar structures deliver high strength accompanied by poor ductility, making it difficult to achieve both properties simultaneously. Secondly, titanium alloys are notoriously difficult to machine. They possess a low thermal conductivity of approximately 7 W/(m·K), merely one quarter of that of steel, alongside high chemical reactivity, which classifies them as hard-to-cut materials. The material utilization ratio of traditional casting and forging processes often exceeds 10:1. Integrated forming of complex components cannot be easily realized, resulting in massive material waste and substantial cost burdens[4].Titanium alloys are sensitive to extreme environments. Under high-strain-rate impacts such as bullet resistance and high-speed collision conditions, adiabatic shear bands are prone to form within titanium alloys, which will lead to catastrophic brittle fracture.[5]。 Under high-temperature and oxygen-rich environments, interstitial solid solution of oxygen tends to induce oxygen embrittlement and drastically degrade ductility[6]. Likewise, titanium alloys face stringent requirements when applied for implantation in the human physiological environment. The elastic modulus of solid titanium alloy implants is approximately 110 GPa, which shows a severe mismatch with that of natural bone ranging from 10 to 30 GPa. This gives rise to the stress shielding effect, which readily causes bone resorption and implant loosening.[1]。

To address the aforementioned limitations, remarkable breakthroughs have been achieved in relevant research over the past five years. Microstructural design has evolved from homogeneous structures to heterogeneous, gradient and metastable configurations, while manufacturing processes have shifted from empirical trial-and-error approaches toward additive manufacturing and digital intelligent control. The application scenarios of titanium alloys have also been greatly expanded, evolving from single structural load-bearing functions toward multi-functional integration such as biological responsiveness and energy storage. Based on the latest cutting-edge advances in titanium alloy research, this paper systematically reviews the field from two core dimensions: microstructure regulation and strengthening-toughening mechanisms, elaborates on the physical nature of property enhancement for titanium alloys, and prospects the routes for their future development.

2. Microstructure Regulation of Titanium Alloys: From Homogeneous Design to Heterogeneous and Metastable Design

Microstructure fundamentally determines the service performance of titanium alloys. Traditional homogeneous equiaxed or purely lamellar microstructures cannot strike a balance between strength and ductility. Nevertheless, recent studies have verified that the construction of heterogeneous structures and metastable phase transformation engineering can drastically improve strength and toughness without an obvious sacrifice in ductility.

2.1 Metastable Configuration and Heterogeneous Lamellar Microstructure

The core of Metastability Engineering lies in adopting stress-induced phase transformations, including transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP), to sustain work-hardening capacity, thereby delaying necking and improving uniform elongation.

Zhang et al. [7] conducted experiments introducing trifunctional nanoprecipitates into metastable β-type Ti-1Al-8.5Mo-2.8Cr-2.7Zr titanium alloy. Nanoscale precipitates were employed for strengthening, and a heterogeneous layered matrix was fabricated via coupled thermomechanical treatment. These precipitates contribute dispersion strengthening and serve as sites for local stress concentration, triggering stress-induced martensitic transformation (SIM α″) within the metastable β matrix to maintain persistent work hardening. Moreover, they impede crack propagation at macroscopic layered interfaces and generate geometrically necessary dislocations,as shown in Figure 1[7]. Experimental results demonstrate that the yield strength of this alloy is doubled compared with conventional coarse-grained equiaxed counterparts, while a considerable uniform elongation is well preserved.

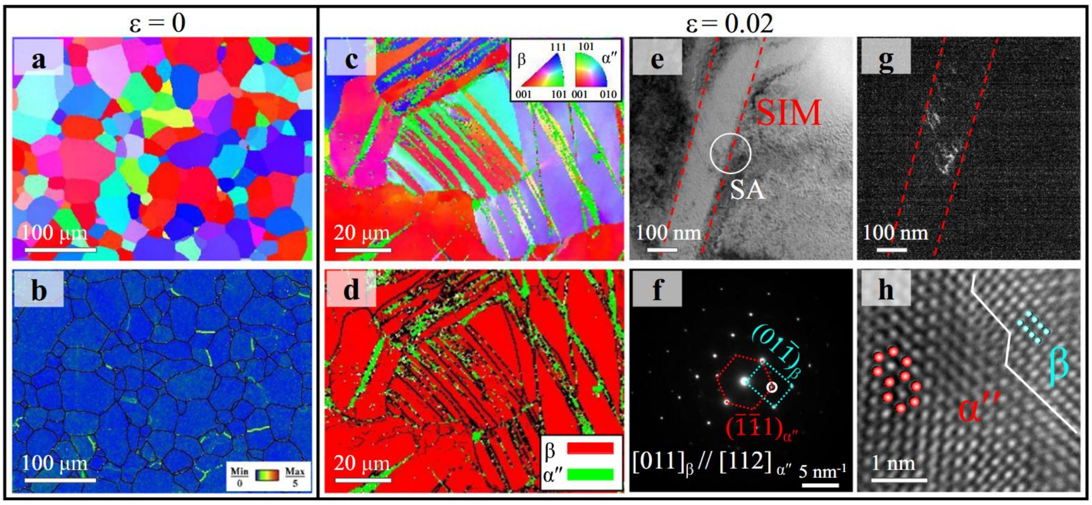

Figure 1[7] Deformation Mechanism of EGS-61 β-Ti Alloy at the Initial Stage of Plastic Deformation

Hu Kongliang et al. [3] further indicated through their research that although nanocrystallized microstructures can further increase yield strength, constructing multi-scale heterogeneous and gradient structures serves as a more reliable strategy to further elevate high-cycle fatigue life and damage tolerance. The physical essence of this effect is the accumulation of geometrically necessary dislocations near heterogeneous interfaces, which gives rise to back-stress hardening. Meanwhile, the interfaces themselves can effectively deflect the propagation path of cracks.

2.2 Microtexture Orientation Regulation

Oxygen-enriched titanium alloys fabricated via powder metallurgy have long been plagued by the trade-off between strength and ductility. Zhang Hairui et al. [7] prepared near-α titanium alloy with an oxygen content of 0.36 wt% through sintering and hot extrusion. By controlling the formation of composite lamellar microstructures, a strong ⟨0001⟩ α microtexture aligned along the extrusion direction was obtained. The alloy maintained an ultimate tensile strength of 1070 MPa, while its elongation was improved from 8.9% to 22.0%(refer to Figure 2[8]). EBSD characterization reveals that this texture activates pyramidal ⟨c+a⟩ dislocations, enhances the deformation compatibility of grain boundaries, and suppresses the early initiation of cracks [7].

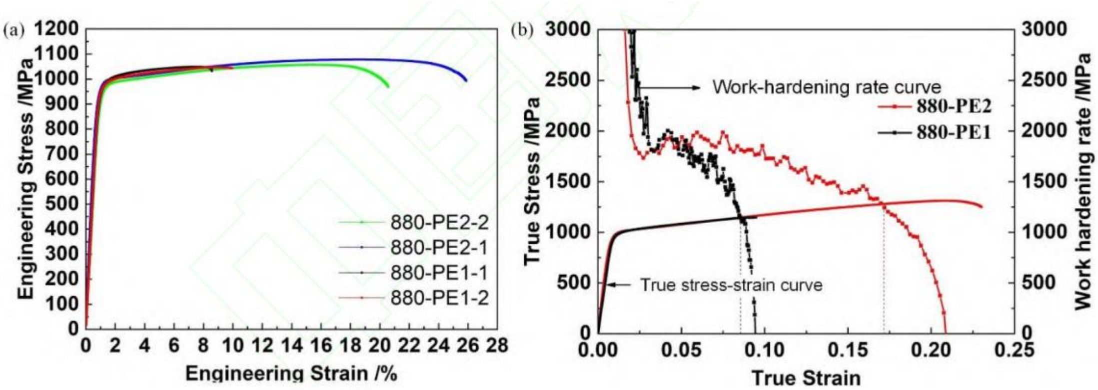

Figure 2 [8](a) Engineering stress-strain curve; (b) True stress-true strain curve and work hardening rate curve

EBSD results demonstrate that the aforementioned texture activates pyramidal ⟨c+a⟩ dislocations. Nevertheless, due to their large Burgers vector and high stacking fault energy, ⟨c+a⟩ dislocations are hardly activated in conventional titanium alloys. After crystal orientation is optimized via intense texture engineering, these dislocations can move in the form of wavy slip, leading to an abnormal rise in work hardening rate, facilitating lamella bending and grain boundary compatible deformation, and accordingly restraining the initiation of intergranular cracks. This study proves that microtexture is not merely a byproduct during material fabrication, but can be adopted as a deliberately designed microstructure optimization strategy to synergistically enhance the strength and toughness of materials.

2.3 Heat Treatment: From Macroscopic Regulation to Nondestructive Intelligent Diagnosis

Heat treatment represents the most mature and cost-effective method to tailor the microstructure of titanium alloys. For Ti-6Al-4V alloy, annealing, solution treatment and aging can adjust the volume fractions of equiaxed, bimodal, Widmanstätten and basketweave microstructures, so as to balance ductility, fatigue performance and fracture toughness [1,2]. Equiaxed microstructure delivers the optimal fatigue life, while basketweave and lamellar structures possess superior creep resistance and fracture toughness.

In recent years, special heat treatment technologies including cyclic heat treatment, field-assisted heat treatment (electromagnetic field, ultrasonic field) and hydrogen treatment have gradually matured. These techniques accelerate elemental diffusion, relieve residual stress within a shorter duration, and realize nanoscale and multi-scale refinement of phase morphologies. Dong Yihao et al. [9] systematically investigated the modification effect of single annealing on the microstructure and residual stress of TC17 titanium alloy fabricated by Wire Arc Additive Manufacturing (WAAM). It is revealed that annealing enables β phases to penetrate and fragment α laths, meanwhile decomposing α′ martensite into stable α+β phases. Ostwald ripening takes place when the annealing temperature rises to 650 °C, which results in the coarsening of α phases. Quantitative analysis verifies that 600 °C is the optimal annealing temperature for the highest degree of microstructure homogenization and effective residual stress release. After annealing, the ultimate tensile strength and yield strength increase from 962.10 MPa and 937.65 MPa to 1078.55 MPa (12.10% increment) and 1060.84 MPa (13.14% increment), respectively [9]. Refer to Figure 3 for the tensile test results of TC17 specimen.[9]

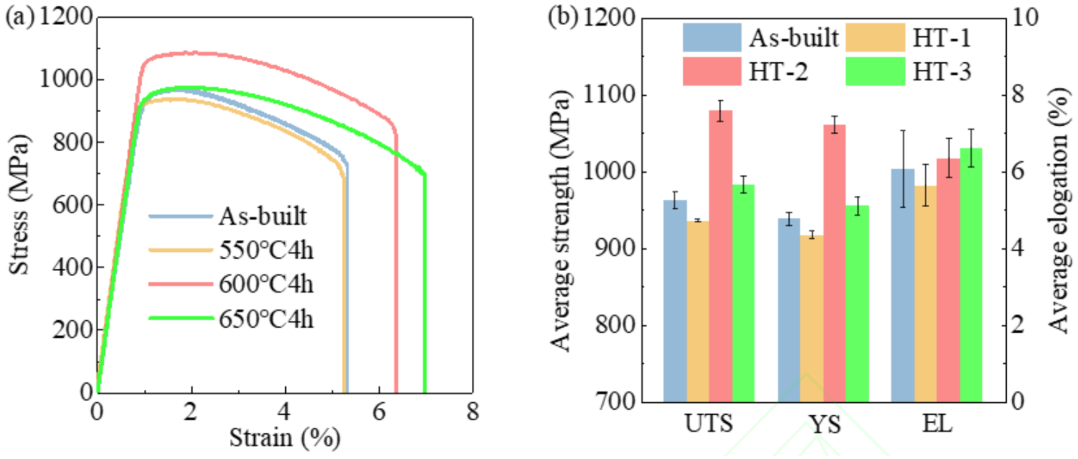

Figure 3 [9]Tensile test results of WAAM-fabricated TC17 specimens subjected to different heat treatments: (a) Engineering stress-strain curves; (b) Statistical analysis of tensile properties

Nevertheless, it is noteworthy that high-throughput non-destructive testing methods have long been lacking for accurately classifying the physicochemical states of each phase inside components after heat treatment. Yang [10] proposed a novel method combining Laser-Induced Breakdown Spectroscopy (LIBS), Independent Component Analysis (ICA) and Deep Neural Networks (DNN), which can precisely classify the microstructure, Vickers hardness and elemental distribution of TC4 specimens after heat treatment. The study reveals that during solution and aging treatment, inhomogeneous elemental distribution and ablation mass differences caused by varying hardness endow LIBS spectra with distinguishable features. This research provides a crucial detection tool for closed-loop control among heat treatment process, microstructure and mechanical properties, and lays a technical foundation for rapid evaluation of strengthening and toughening mechanisms in follow-up work.

3. Strengthening and Toughening Mechanisms of Titanium Alloys: From Dislocation Behavior to Dynamic Failure Control

The previous section elaborated on how to tailor microstructures, while this section further illustrates how these microstructures achieve strengthening and toughening. The essence of strengthening and toughening mechanisms lies in regulating the microscopic processes of deformation and fracture, including dislocation slip, twinning, phase transformation, as well as crack initiation and propagation.

3.1 Phase Transformation and Nanocrystallization under Dynamic Loading

Under high-strain-rate service conditions such as high-speed impact and explosion, plastic work cannot be dissipated in a timely manner, and Adiabatic Shear Bands (ASBs) are prone to form inside titanium alloys. During high-speed impact, the work generated by intense local plastic deformation fails to diffuse promptly and induces sharp temperature rise. At the initial stage, the material dissipates external impact energy via non-equilibrium microstructure evolution following the path: β matrix → α″ martensite → nano-twins → hexagonal α phase. Nevertheless, with the increase of true strain, grains within shear bands undergo nanocrystallization accompanied by dynamic recovery and softening, resulting in the collapse of flow stress. At this moment, adiabatic thermal softening outweighs strain hardening, concentrating deformation drastically toward the core of shear bands. Microvoids and microcracks preferentially nucleate inside or at the boundaries of softened shear bands, eventually driving catastrophic brittle fracture along fluid-like shear paths. In summary, ASBs serve as the primary inducement for catastrophic fracture of titanium alloys under dynamic loading.

Guan et al. [5] carried out systematic HRTEM characterizations on the microstructure evolution of Ti-10V-2Fe-3Al alloy under dynamic loading at elevated temperatures. The alloy exhibits a coarse single-phase β microstructure after solution treatment, and displays distinctive double yielding and abrupt stress drop under dynamic loading. Stress-induced martensitic transformation together with the generation of nano-twins inside martensite accounts for the double yielding phenomenon, whereas thermal softening originating from dynamic recovery dominates the subsequent sharp decline in stress.

A multi-stage energy dissipation mechanism within the central region of ASBs is identified(Refer to Figure 4[5]). Stress first triggers the formation of face-centered orthorhombic α″ martensite, followed by the generation of type I nano-twins on the {111} crystal planes within α″ martensite. Eventually, α″ martensite further transforms into stable hexagonal close-packed α phase, with a strict crystallographic orientation relationship between the two phases

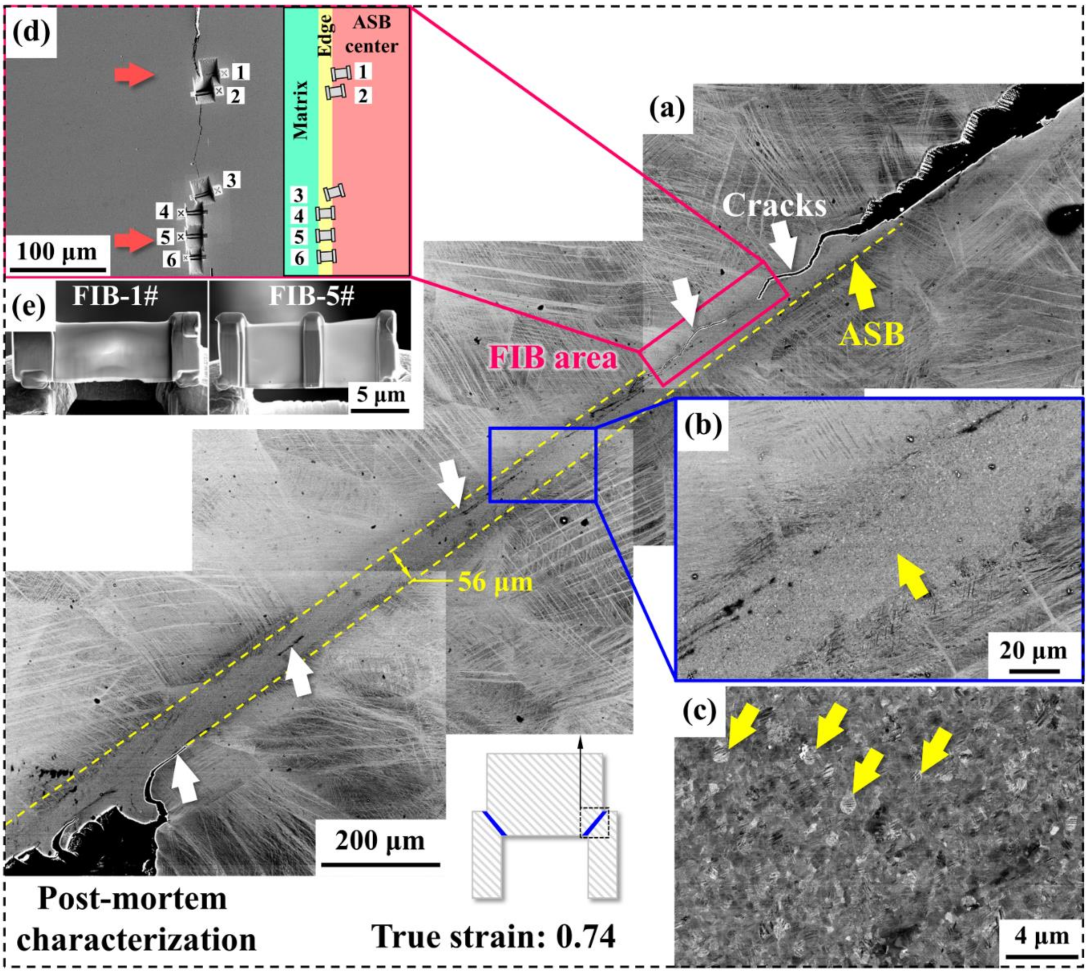

Figure 4 [5] (a) Low-magnification BSE image of the ASB; (b) High-magnification BSE image of the ASB; (c) Further magnified view at the center of the ASB (the area indicated by the arrow in (b)); (d) SE image of the FIB-milled region and schematic diagram of the FIB specimen at the selected position; (e) SE images of Specimen FIB-1 and Specimen FIB-5.

This series of microstructure evolution essentially serves as a mechanical energy dissipation mechanism. External impact energy is converted into interfacial energy via phase transformation, twinning and grain refinement, thereby delaying macroscopic fracture. This offers a novel design strategy for impact-resistant titanium alloys; promoting stress-induced phase transformation and nanocrystallization can effectively enhance dynamic toughness.

3.2 Crack Initiation and Propagation under Room-Temperature Impact Toughness

Impact toughness acts as a core design indicator for titanium alloys applied in dynamically loaded structures such as ship components, aircraft landing gears and armor plates. Zhao Runze et al. [11] illustrated that alloying elements and microstructural features govern dislocation activation, deformation twinning as well as crack initiation and propagation paths, which jointly determine the room-temperature impact toughness.

The core viewpoint summarized by Zhao Runze et al. [11] is that the volume fraction and morphology of the α phase constitute the primary factor influencing impact toughness. Equiaxed α grains are beneficial for increasing crack initiation energy, while lamellar α structures deliver superior resistance against crack extension. Additionally, the stability of the β phase also affects deformation mechanisms. Metastable β phase tends to undergo stress-induced martensitic transformation upon impact to absorb fracture energy. There exists an optimal range for grain size: excessively coarse grains reduce crack initiation energy, whereas overly refined grains weaken crack propagation resistance.

Accordingly, the optimization of impact toughness requires a trade-off between inhibiting crack nucleation and slowing crack growth, rather than simply maximizing a single performance metric. This bears analogous logical characteristics to the strength–ductility trade-off observed in static tensile tests.

3.3 Activation of Dislocation Behavior under Oxygen-Enriched Conditions

As elaborated in Section 2.2, the research by Zhang Hairui et al. [8] revealed the modulation effect of microtexture on dislocation modes and addressed the long-standing issue of whether oxygen embrittlement can be mitigated.

In conventional oxygen-rich titanium alloys, oxygen atoms occupy interstitial lattice sites and severely hinder dislocation motion, resulting in localized stress concentration and premature fracture. Nevertheless, within regions with ⟨0001⟩ α texture, pyramidal ⟨c+a⟩ dislocations are activated and migrate via wavy slip. Unlike basal ⟨a⟩ and prismatic ⟨a⟩ dislocations, ⟨c+a⟩ dislocations are capable of accommodating strain along the c-axis. Their wavy slip morphology indicates undulating movement within slip planes, raising the probability of dislocation interactions and consequently elevating the work hardening rate.

This finding complements the strategy proposed by Song et al. [6] for avoiding oxygen embrittlement via non-equilibrium solidification in additively manufactured Ti–O–Fe alloys. The former retains oxygen within the matrix yet triggers mobile dislocations through texture engineering, while the latter homogenizes oxygen distribution to eliminate localized embrittlement. These two approaches are respectively applicable to powder metallurgy and additive manufacturing routes, collectively proving that the detrimental embrittlement effect of oxygen can be suppressed through microstructure tailoring.

3.4 Strengthening-Toughening Challenges and Heat Treatment Regulation of Additively Manufactured Titanium Alloys

Owing to the steep thermal gradient during layer-by-layer deposition, as-built microstructures generally consist of epitaxially grown coarse primary β columnar grains with strong ⟨001⟩ orientation, fine lamellar α or acicular α′ martensite, accompanied by considerable residual stress [12,13]. Such microstructures directly lead to mechanical anisotropy and degraded fracture toughness.

Zhang Fengying et al. [13] reviewed heat treatment schemes for laser additively manufactured titanium alloys, emphasizing that the selection of stress-relief annealing, sub-β or super-β transus annealing, solution and aging treatment, as well as Hot Isostatic Pressing (HIP) must be customized according to practical service requirements of components. Three primary strategies are summarized as follows:

1) Stress-relief annealing combined with sub-β annealing is preferred for superior fatigue resistance to preserve fine equiaxed microstructures;

2) Super-β transus annealing is adopted to produce coarse lamellar or basketweave structures for improved high-temperature creep resistance;

3) Solution and aging treatment is employed to adjust the α/β phase ratio and precipitate secondary α phases for balanced strength and ductility.

The essence of this process design is to further optimize and regulate the inherently non-equilibrium solidification microstructures formed during additive manufacturing via post-heat treatment, so that the final microstructure evolves toward targeted service performances.

4. Conclusions and Outlook

From the two perspectives of microstructure regulation and strengthening-toughening mechanisms, this paper systematically reviews recent progress in performance enhancement of modern titanium alloys. The main conclusions are drawn as follows:

(1) Heterostructure design and metastable phase transformation effectively break the strength–ductility trade-off. By constructing heterogeneous layered structures coupled with trifunctional nanoprecipitates in Ti-1Al-8.5Mo-2.8Cr-2.7Zr alloy, Zhang et al. [14] doubled the yield strength compared with traditional counterparts while maintaining favorable ductility. This strategy relies on back-stress hardening generated at heterogeneous interfaces and sustainable work hardening supplied by metastable phase transformations.

(2) Interstitial solid solution and microtexture orientation optimization redefine the permissible threshold of impurity elements. Song et al. [6] verified that ultrafast solidification enables atomic-level homogeneous dissolution of oxygen to eliminate oxygen embrittlement in additively manufactured Ti–O–Fe alloys. Zhang Hairui et al. [8] further demonstrated that ⟨0001⟩ α texture activates pyramidal ⟨c+a⟩ dislocations and restores ductility in oxygen-rich systems. The embrittlement induced by oxygen can be suppressed via microstructure control, with the key lying in manipulating oxygen distribution and dislocation mobility.

(3) Guan et al. [5] confirmed that phase transformation and nanocrystallization under dynamic loading constitute an intrinsic energy dissipation mechanism. The integrated microstructure evolution involving α″ martensitic transformation, nano-twinning and grain refinement within adiabatic shear bands of Ti-10V-2Fe-3Al provides explicit microstructural criteria for designing impact-resistant titanium alloys.

(4) Additive manufacturing paired with customized heat treatment serves as an effective route to strengthen and toughen complex components. Dong Yihao et al. [9] achieved simultaneous improvement in strength and ductility for WAAM-produced TC17 alloy through annealing at 600 ℃, while Zhang Fengying et al. [13] established a systematic heat treatment roadmap for laser additively manufactured titanium alloys oriented toward diverse service demands.

In light of these conclusions, higher standards have been put forward for the application of next-generation titanium alloys amid technological advancement. Several suggestions and prospects for the future development of titanium alloys are proposed below:

(1) As aforementioned, heterostructure engineering and oxygen distribution control are critical to overcome the strength–ductility paradox. However, quantitative criteria to modulate back stress at heterogeneous interfaces and dislocation activation energy remain insufficient. Future research shall deeply integrate machine learning, phase-field simulation and finite element analysis to establish high-throughput correlations among chemical composition, fabrication process, microstructure and mechanical properties. Conventional trial-and-error post-processing will be upgraded to targeted microstructural phase transformation pathways tailored for specific service environments such as anti-impact and anti-fatigue scenarios.

(2) Although additive manufacturing and personalized heat treatment can markedly boost mechanical properties, non-equilibrium phase transitions during the forming of intricate components tend to introduce localized microstructural defects. Hence, real-time defect compensation and full-process intelligent manufacturing of microstructures are urgently required. It is imperative to develop an online intelligent quality control system integrating shape and microstructure control, which incorporates in-situ sensing techniques including LIBS and infrared thermal imaging to dynamically capture macroscale and microscale defects. Combined with adaptive algorithms, active regulation and compensation of microstructures can be realized to eliminate property fluctuations and realize high-precision forming and qualified mechanical performance of large-scale components.

(3) Benefiting from microstructure modification and interstitial solid solution regulation such as ductility recovery in oxygen-containing alloys, modern titanium alloys possess excellent fundamental mechanical properties, laying a solid foundation for their transformation from high-specific-strength structural metals to intelligent multifunctional metals. Future studies should fully exploit the geometric design freedom of additive manufacturing, together with surface modification and gradient microstructure engineering, to expand applications toward multi-functional fields including biomedicine (low-modulus substrates and bio-responsive surfaces) and electrochemical energy storage (corrosion-resistant conductive bipolar plates).

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