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Fatigue in metals and alloys

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Fatigue failure in metals remains a concern across engineering disciplines, substantially influencing the design, reliability and economic viability of essential load-bearing structure components. Despite notable advances in materials science, fatigue-induced failures—particularly in extreme applications such as deep-space exploration—continue to pose challenges owing to their inherent complex and unpredictable nature. This Perspective provides a concise overview of emerging frontiers in improving fatigue resistance, along with key advancements in our understanding of metal fatigue. It also explores current opportunities and challenges, ranging from the development of promising fatigue-resistant materials through spatially heterogeneous composition and microstructure design to innovations in testing methods, characterization techniques, theoretical frameworks and modelling methodologies for metal fatigue.

Cyclic fatigue is a critical factor influencing the performance and reliability of metallic materials, and also has a role in determining the safety and lifespan of structural components subjected to repeated stress or strain cycles[1–3]. In industries such as aerospace, automotive and civil engineering, metallic structures and components are typically exposed to alternating loads that progressively accumulate microscopic damage[1,3]. Over time, this exposure can trigger the initiation and propagation of fatigue cracks, leading to sudden and catastrophic failure, even at stress levels well below the material's ultimate tensile strength (σ_{UTS})[1,4]. A notable example is the 1950 Comet aircraft disasters, where an early commercial jet airliner suffered mid-air breakups owing to fatigue failure caused by repeated pressurization and depressurization cycles, resulting in the loss of hundreds of lives[1].

The economic and societal impact of metal fatigue failures—and the measures taken to prevent them—are substantial, accounting for a considerable portion of annual gross national product in industrialized nations. To address these challenges, materials scientists have focused on developing innovative, high-performance metals with enhanced fatigue resistance[3,5]. These efforts aim to improve structural reliability, mitigate failure risk and promote long-term cost efficiency. In the following sections, we overview landmarks in metal fatigue research and recent advances in fatigue performance. Finally, we outline opportunities and challenges in the pursuit of metallic materials with superior fatigue resistance.

Historical review of fatigue approach establishment

Since the 1830s, fatigue analysis has evolved from an largely empirical practice into a rigorous scientific discipline[6–8]. Key contributions include the development of the stress-controlled and strain-controlled fatigue methodologies[6,9–11], and basic fatigue principles[12–18]. The stress-based method introduced by A. Wöhler in 1860[6] and formalized by O. H. Basquin in 1910[9] plots stress amplitude ($\Delta\sigma/2$) against number of cycles to failure (N_f), usually referred to as an S–N curve. This approach establishes the concept of fatigue endurance strength, σ_{-1}, denoting the stress threshold below which a material can withstand at least 10^7 cycles without failure under standard laboratory fatigue testing[9]. With the advent of modern applications requiring components to endure very-high-cycle fatigue ($N_f > 10^9$), such as aerofoils in aero-engines, combustion engine cylinders and high-speed train bearing axles, the study of very-high-cycle fatigue has gained prominence since 1990[19,20].

In parallel with the achievements in the stress-based method, L. F. Coffin and S. S. Manson independently demonstrated in 1953[10,11] that fatigue life is also governed by plastic strain amplitude under strain-controlled fatigue testing. During such tests, a dynamic extensometer is mechanically clamped onto the specimen surface to directly measure and control fatigue strain in a closed-loop system. This discovery identifies plastic strain as a crucial factor in cyclic damage, leading to the formulation of the Coffin–Manson law. This law relates plastic strain amplitude ($\Delta\varepsilon_{pl}/2$) to N_f, forming the foundation for strain-based

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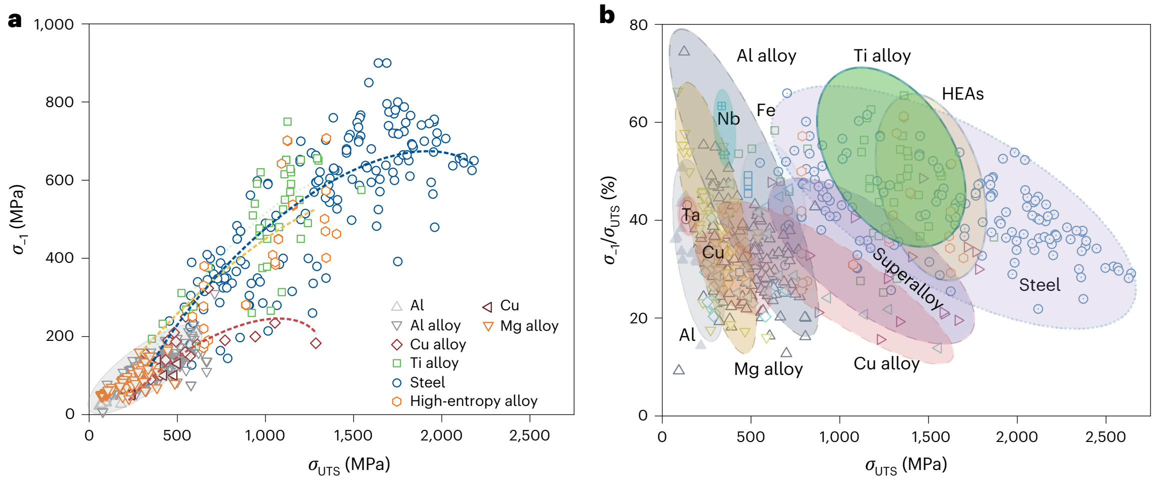

Fig. 1 | Relationship between fatigue strength and tensile properties. **a**,**b**, Dependence of fatigue strength (σ_{-1}) under tension–compression fatigue tests at room temperature on ultimate tensile strength (σ_{UTS}) (**a**), and fatigue strength normalized by σ_{UTS} as a function of σ_{UTS} for various pure metals and alloys[21–25] (**b**). The dashed curves in **a** denote the evolution trend of fatigue strength as a function of σ_{UTS} for typical metals in different strength levels, including Cu alloys, high-entropy alloys (HEAs) and steels.

fatigue life characterization in the low-cycle regime ($N_f < 10^5$)[1,2]. Building on these findings, J. D. Morrow in 1964 explored the cyclic stress response of metals—encompassing hardening, softening and saturation—using strain-controlled fatigue tests[12]. This work advanced the microstructural understanding of fatigue behaviour. Together, stress- and strain-controlled fatigue testing methodologies provide complementary frameworks for characterizing fatigue properties, supporting the development and optimization of engineering metallic materials.

Fatigue properties

Compared with tensile testing, cyclic fatigue analysis is more complex and time consuming. This complexity has promoted engineers to explore whether fatigue resistance can be reliably predicted from simple uniaxial tensile properties using statistical data from various materials. The answer, however, is not straightforward. Over the past decades, extensive effort has investigated how material properties, particularly σ_{UTS}, influence the fatigue behaviour of pure metals[21], alloyed materials[21–24] and high-entropy alloys[25]. Fatigue strength generally increases proportionally with σ_{UTS} within specific metals or alloy systems (Fig. 1a). The proportionality is largely attributed to the improved resistance to plastic deformation, that is, restricting dislocation motion and the retention of cyclic elasticity with minimal plastic deformation as σ_{UTS} increases[4,26]. However, in most materials, such as Cu alloys and steels, σ_{-1} plateaus or even decreases when σ_{UTS} exceeds certain thresholds (for example, ~1,500 MPa for steels[22]). This non-positive relationship indicates a deviation from the expected strengthening–fatigue correlation.

Additionally, fatigue efficiency, the ratio of σ_{-1} to σ_{UTS}, typically decreases with higher σ_{UTS}, in some cases falling below 0.2 or so (Fig. 1b). This trend underscores the limitations of conventional alloying approaches for substantially improving σ_{-1} and highlights the persistent challenge of addressing low fatigue efficiency in high-strength materials. Consequently, relying solely on tensile strength to predict fatigue failure remains unreliable, highlighting the need for additional strategies to more accurately assess and enhance fatigue resistance in material design.

Fatigue strength and fatigue life are the two critical concepts in evaluating a material system's resistance to fatigue. Fatigue life refers to the number of loading cycles that a specimen can endure before failure under specific conditions. This has led to a common misconception that either fatigue strength or fatigue life can independently assess a material's fatigue resistance. However, unlike fatigue strength, which is determined solely through stress-based methods, fatigue life is usually evaluated using both stress- and strain-based methods and is considered a more critical parameter, as it is highly sensitive to varying stress and strain conditions and intrinsic material properties[1]. For instance, the fatigue life evaluated using these two methods is typically applicable to materials free from defects or flaws, where the critical number of fatigue cycles during crack initiation accounts for 80–90% or more of the total fatigue life. Conversely, for engineering components containing crack-like defects, fatigue life is predominantly governed by crack propagation. In such cases, defect-tolerant approaches based on fracture mechanics become essential[27].

Generally, materials exhibit elastic deformation under low-stress fatigue conditions, where failure life strongly correlates with material strength. In contrast, under high-stress fatigue conditions, fatigue life primarily depends on ductility, as higher stress levels induce significant plastic deformation. When measured in stress- or strain-controlled tests, a natural 'banana-shaped' trade-off emerges between fatigue strength and fatigue life for most materials (Fig. 2). This conflict primarily arises from the inherent trade-off between strength and ductility, commonly observed in uniaxial tensile tests.

An example lies in face-centred cubic Cu, which has been extensively studied as a model metal in fatigue research[2,16,17] (Fig. 2). In coarse-grained Cu, the lower strength enables greater plastic deformation, resulting in shorter N_f and low σ_{-1} (~50 MPa) under stress-controlled conditions (Fig. 2a). However, coarse-grained Cu exhibits superior fatigue life under $\Delta\varepsilon_{pl}/2$ due to its excellent ductility (Fig. 2b). Grain refinement via high-angle grain boundaries can effectively enhance high-cycle fatigue strength[28–30]. Ultrafine-grained Cu, prepared by severe plastic deformation, exhibits elevated σ_{-1} of 80–100 MPa due to increased strengths and suppressed dislocation motion[30]. Unfortunately, under low-cycle conditions, ultrafine-grained Cu exhibits severely reduced fatigue life—less than 20% of coarse-grained Cu at high strain amplitudes[30,31].

While the inherent conflict between fatigue strength and fatigue life remains a challenge, strategic manipulation of structural features, defect distribution and microstructural heterogeneity can achieve a balance between these properties somewhat, leading to unique and superior fatigue behaviours[32]. A notable example is in nanotwinned metals, which feature a high density of nanoscale coherent twin boundaries within micrometre-sized grain interiors[33]. This structure imparts exceptional properties, including high strength, good tensile ductility, excellent electrical conductivity and thermal stability[33]. Highly

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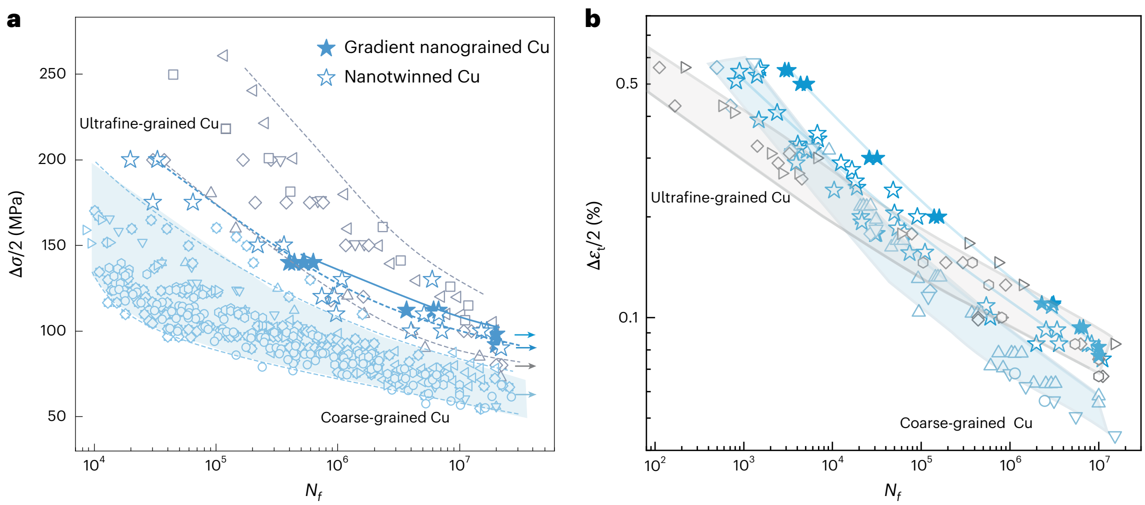

Fig. 2 | Fatigue life under stress and strain control. a,**b**, Dependence of the fatigue life (N_f) on $\Delta\sigma/2$ (**a**) and on the total strain amplitude ($\Delta\varepsilon_t/2$) (**b**) for pure Cu with various microstructures, such as coarse grains[21], ultrafine grains[18,30,54], nanotwinned grains[34] and gradient nanograins[32]. The hollow symbols in light grey denote the fatigue data of ultrafine-grained Cu, while the hollow symbols in light blue denote the fatigue data of coarse-grained Cu.

oriented nanotwinned Cu exhibits fatigue strength comparable to that of ultrafine-grained Cu (90 MPa) and fatigue life comparable to that of coarse-grained Cu at the same $\Delta\varepsilon_{pl}/2$ (ref. 34) (Fig. 2), breaking the traditional trade-off between fatigue strength and life.

Another strategy is to engineer gradient nanostructures in materials. Gradient nanograined Cu features a spatial gradient grain size distribution from nanocrystalline grains to coarser grains in the top surface of about 100–200 µm by surface mechanical treatment[35]. This unique architecture delivers a high fatigue strength of 98 MPa, a fatigue efficiency of 0.4 and fatigue lifetimes double those of coarse-grained counterparts at the same total strain amplitudes[32] (Fig. 2b). Similar trends are observed in other gradient nanograined engineering alloys[36].

Fatigue mechanisms

The microscopic mechanisms of metal fatigue failure are inherently sophisticated, involving processes such as cyclic strain localization, damage accumulation, structural evolution, and crack nucleation and propagation under varying fatigue conditions (Fig. 3)[17,37]. Since 1903, with the observation of slip bands and cracks developing on specimen surfaces under cyclic loading[7], the fundamental mechanisms of metal fatigue have drawn increasing interest[8]. Specially, multiscale characterization techniques, particularly high-resolution electron microscopy combined with digital image correlation and focused ion beam nanofabrication developed during recent decades, have provided useful structural insights and helped to address long-standing fundamental questions related to fatigue in structural materials[38–40]. The mechanisms of crack initiation and propagation can be found in the relevant literature for foundational insights[41–45].

Cyclic strain localization is a hallmark of metal fatigue[2,17]. Unlike monotonic tensile loading, cyclic plastic strain ($\Delta\varepsilon_{pl}/2$) during fatigue loading is relatively small, comparable to the elastic strain component ($\Delta\varepsilon_e/2$), but cyclic slip becomes readily irreversible during loading–unloading cycles. Despite its small magnitude, cyclic plastic strain accumulates over thousands to millions of fatigue cycles, with total accumulated strain ($\sum 4\,\Delta\varepsilon_{pl}/2$) at a high level of three orders of magnitude higher than tensile strain[2], inevitably inducing microstructural evolution. Features of single-slip-induced heterogeneous dislocation patterns, such as persistent slip bands with ladder structure, and veins, are commonly observed in coarse-grained and monocrystalline Cu under low cyclic stress[46] (Fig. 3a,b). At higher cyclic stresses or strains, dislocation patterning evolves into multislip cells, dynamically rearranged from densely packed dislocation dipoles[18,47]. This process, regarded as autonomous and self-organizing structural evolution, usually minimizes free energy[2,17].

Micrometre-scale surface slip extrusions rapidly form following dislocation patterning, driven by extensive dipole multiplication, annihilation and vacancy production, as suggested by computational and theoretical studies such as the semi-quantitative Essmann–Gösele–Mughrabi model[48–50]. Fatigue-induced extrusions, along with intrusions and surface roughening, stem from irreversible slip, with partial slip reversibility during loading reversal[23,51] (Fig. 3c,d). Consequently, fatigue cracks typically initiate at the free surface, along either the extrusions or intrusions, or at grain boundaries with dislocation pile-up[42–44,52]—thereby reducing high-cycle fatigue strength.

These cumulative, irreversible fatigue damages are strongly influenced by the characteristic length scale of fatigued specimens, such as grain size or film thickness[30,53]. For example, surface relief decreases monotonically with the refinement of grain size and film thickness to submicrometre and nanometre scales, with damage primarily localized at interfaces or grain boundaries[2,53]. At such small length scales, dislocation motion is suppressed, and the typical dislocation patterns, such as cells or walls commonly observed in fatigued coarse-grained metals, no longer form[30]. Fatigue mechanisms shift from dislocation patterning to interface-dominated behaviours, including macroscopic shear banding and/or localized abnormal grain coarsening (Fig. 3e), driven by limited strain hardening, reduced ductility and intrinsic structural instability inherent to grain boundaries[30,54]. These localized damage mechanisms contribute to shorter fatigue life (Fig. 2b) and varying degrees of cyclic softening (Fig. 3f)[30,54].

Suppressing cyclic strain localization remains a challenge, especially for high-strength materials[55–57]. Highly oriented nanotwinned Cu shows a unique history-independent, stable cyclic response due to the formation of reversible superstable correlated necklace dislocations[55]. Spatial gradient microstructures also effectively delocalize cumulative strain and suppress damage accumulation[58]. In gradient nanograined Cu subjected to fatigue tests (Fig. 3g), both gradient elastic and plastic strain amplitudes initially form spatially along the depth (Fig. 3h). During subsequent cyclic deformation, ordered, progressive plastic yielding and elastic–plastic deformation transformation occurs within the gradient nanostructure. A larger $\Delta\varepsilon_{pl}/2$ progressively propagates from coarse grains in the core towards the subsurface ultrafine-grained and surface nanograined regions, effectively counteracting the traditional cyclic strain localization in homogeneous structures.

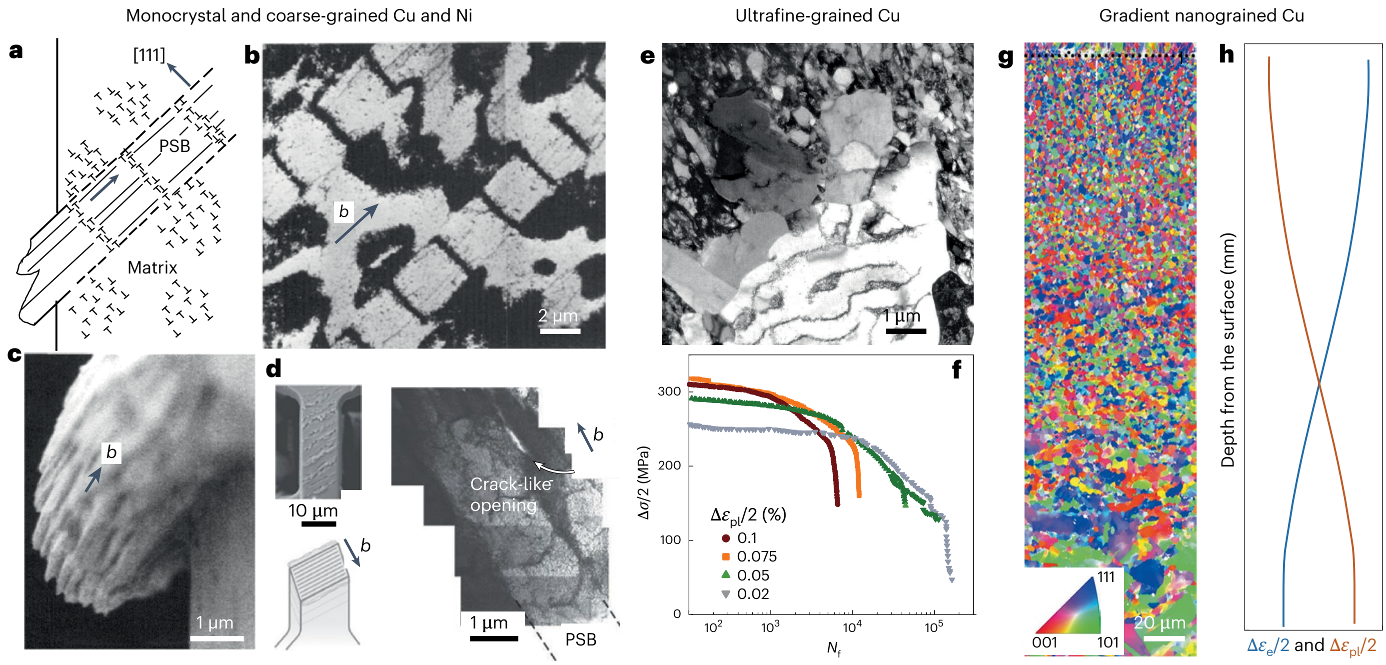

Fig. 3 | Fatigue mechanisms of pure Cu with various microstructures. **a**, Fatigue mechanisms in monocrystal and coarse grains, including the dislocation-slip-induced surface roughening models[49]. PSB, persistent slip band. **b**,**c**, Transmission electron microscopy image of typical persistent dislocation patterns in fatigued Cu single crystal[52] (**b**) and surface roughening revealed by scanning electron microscopy[94] (**c**). **d**, In situ microfatigue experiments on Ni single crystals showing the surface slip markings. A transmission electron micrograph (right) confirms the presence of the ladder-like self-organized persistent slip bands with cracking[46]. **e**,**f**, Fatigue behaviour in conventional ultrafine-grained Cu, showing typical abnormal grain coarsening (**e**) and cyclic softening response (**f**)[31]. **g**,**h**, Controlled homogeneous grain coarsening in surface gradient nanograined layer (**g**) and gradient-distributed cyclic strain (**h**) in gradient nanograined Cu under cyclic loading[32,58]. Figure adapted with permission from: **a**, ref. 49, Taylor & Francis; **b**, ref. 52, ASTM International; **c**, ref. 94, Taylor & Francis; **d**, ref. 46, AAAS; **e**,**f**, ref. 31, Taylor & Francis; **g**, ref. 32, Elsevier; **h**, ref. 58, Elsevier.

Similarly, metastable nanolaminated multiphase steels also exhibit enhanced crack resistance mechanisms, including transformation, and roughness-induced crack termination, under cyclic deformation[32,56]. The above examples demonstrate that non-alloying approaches based on heterostructure design can mitigate localized cyclic strain and suppress damage accumulation, enabling unprecedented resistance to both low-cycle and high-cycle fatigue.

Cyclic strain localization in alloy materials under fatigue is influenced by various microstructural features, including solute distribution and the presence of strengthening precipitates[1]. These obstacles impede dislocation glide and cross-slip, often promoting planar slip, enhancing both strength and fatigue strength[13,59] (Fig. 1a). In conventional solid-solution alloys with low stacking fault energy, planar arrays of well-aligned dislocations tend to persistently localize strain along specific soft planes under cyclic loading (Fig. 4a)[59]. For fatigued precipitation-hardened alloys, dislocation–precipitate interactions are strongly influenced by precipitate characteristics and slip mode: wavy-slip alloys with fine particles favour dislocation bypass, while planar-slip alloys with large shearable precipitates facilitate cutting-through mechanisms (Fig. 4b)[8]. The latter usually display the most pronounced cyclic strain localization[2]. Additionally, incoherent phase boundaries are also prone to stress concentration and early cracking under cyclic loading due to geometrical incompatibility and high interfacial energy[2,8,59]. These factors collectively contribute to reduced fatigue performance in high-strength alloys (Fig. 1b).

Despite ongoing challenges in accurately predicting fatigue damage and failure, nanometre-resolution digital image correlation was recently employed to quantitatively assess slip localization on the surface of various slip-dominated alloys (Fig. 4c)[23]. These localized slip events are highly sensitive to the crystal structures (Fig. 4d). Notably, the degree of plastic localization and slip amplitude observed during the first cycle reflects the material's tendency for cyclic irreversibility and shows a positive, linear correlation with both yield strength and fatigue strength. This finding provides a physical basis for the empirical Basquin law and offers a pathway for predicting fatigue strength and identifying fatigue-resistant alloys.

Unlike room-temperature fatigue, where plasticity solely dominates, high-temperature fatigue of superalloys in service often involves creep–fatigue interaction, oxidation-induced damage and microstructural degradation[60–62]. Damage typically initiates at grain boundaries or oxidized surfaces, with fatigue resistance governed by their microstructural stability, creep strength and oxidation resistance. For instance, well-aligned cuboidal γ′ (Ni_3Al) nanoprecipitates coarsen rapidly under prolonged high-temperature fatigue, accompanied by dislocation accumulation at phase interfaces (Fig. 4e), thereby leading to remarkably reduced precipitation strengthening[63,64]. The interplays of fatigue, creep and oxidation interactions, especially under thermomechanical fatigue conditions, accelerate structure instability and localized damage[64–67].

Spatially heterogeneous microstructures have been effectively applied in nickel-based superalloy discs with graded structures: fine grains in the bore for strength and fatigue resistance at lower temperature, and coarse grains in the rim for enhanced creep and dwell crack resistance at high temperature[68,69]. Similarly, hierarchical structures, such as layered metal–ceramic composites or varying microstructures, offer an improved fatigue resistance and fracture toughness. Layered interfaces tend to resist crack initiation through stress shielding and redistribution across alternating layers, reducing local stress amplitude[70]. Once a crack nucleates, its growth is hindered by interface-induced toughening mechanisms such as crack tip blunting, crack deflection and bridging, and interfacial delamination[70,71].

Environmental factors, such as oxygen and hydrogen in aero-engines or chloride-containing seawater in naval applications,

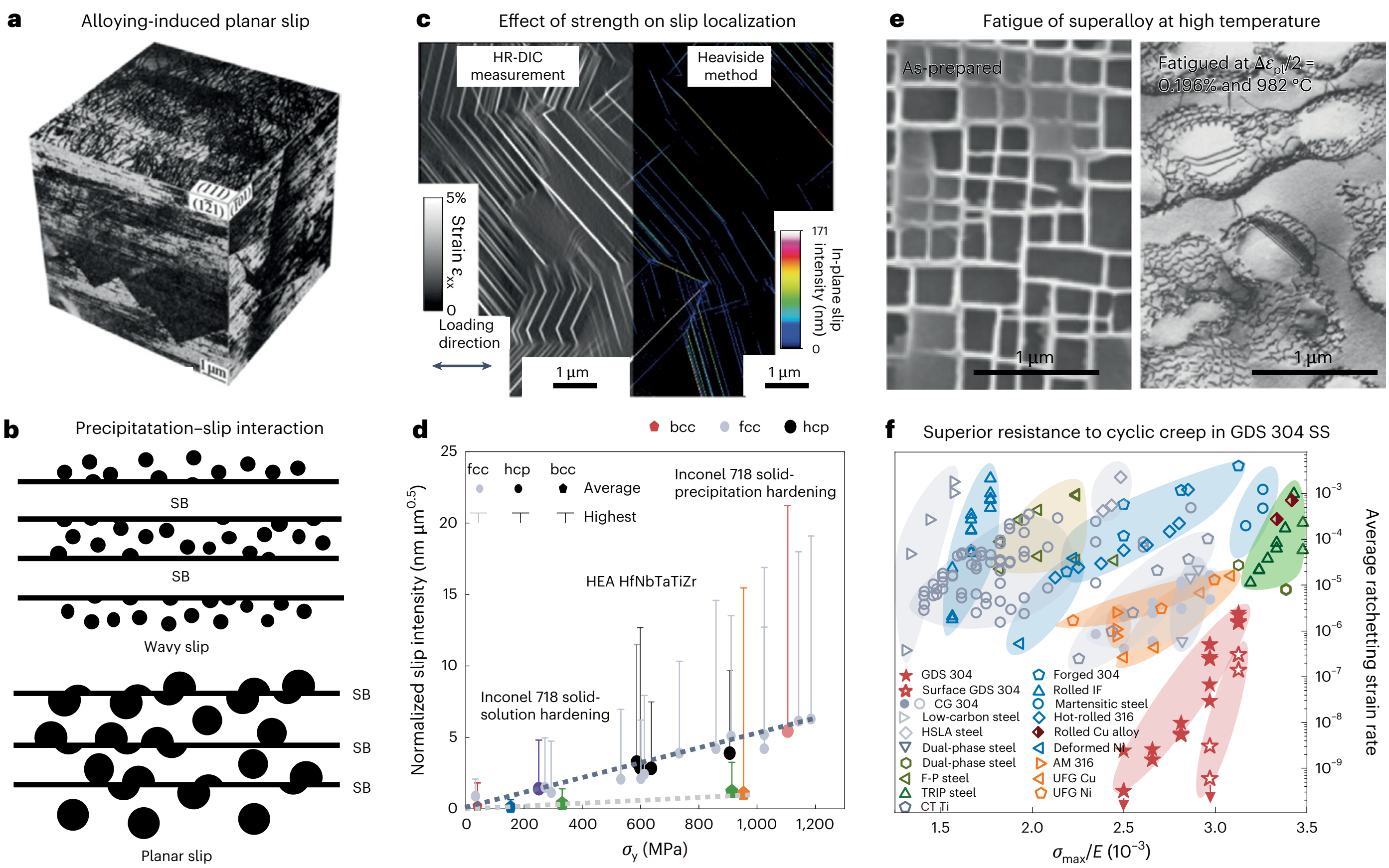

Fig. 4 | Fatigue mechanisms of alloys. a, Typical 3D view of planar-slip dislocation structure of fatigued Cu–Al alloys[59]. **b**, Schematics of slip band (SB)–precipitate interactions: wide slip bands in wavy-slip alloys with small coherent precipitates (top), and narrowed slip bands in planar-slip alloys with large precipitates (bottom)[8]. **c**, Quantitative measurement of surface slip localization in Ni-based superalloy, through conventional strain field obtained by high-resolution digital image correlation (HR-DIC, left) and the discontinuity-tolerant Heaviside digital image correlation method under scanning electron microscopy (right)[23]; **d**, Normalized slip intensity at 0.2% applied macroscopic plastic strain as a function of the yield strength (σ_y)[23]. bcc, body-centered cubic; fcc, face-centered cubic; hcp, hexagonal close-packed. **e**,**f**, Fatigue of alloys in harsh environments. Panel **e** shows transmission electron microscopy images comparing the as-prepared (left) and the coarsened cuboidal γ′ precipitates in René 80 fatigued at a fixed $\Delta\varepsilon_{pl}/2$ of 0.196% and at 982 °C (right)[63,64]. Panel **f** shows combinations of the average ratcheting strain rate and maximum stress σ_{max} normalized by Young's modulus E for gradient-dislocation-structured (GDS) 304 stainless steel (SS) samples compared with stainless steels having homogeneous and heterogeneous microstructures, as well as representative structural materials[76]. The unit for strain rate in **f** is per cycle. HSLA steel, high-strength low-alloy steel; UFG Cu, ultrafine-grained Cu; CT Ti, commercially pure Ti; rolled IF, rolled interstitial-free steel. Figure adapted with permission from: **a**, ref. 59, Elsevier; **b**, ref. 8, Springer Nature Limited; **c**,**d**, ref. 23, AAAS; **e**(left), ref. 64, Chinese Academy of Sciences; **e**(right), ref. 63, Springer Nature Limited; **f**, ref. 76, AAAS.

significantly aggravate fatigue through mechanisms such as corrosion fatigue, stress corrosion cracking, oxidation fatigue and hydrogen embrittlement[5,67,72,73]. These effects promote stress and strain localization and accelerate crack initiation and growth, underscoring the need to integrate environmental effects into fatigue fracture models and design strategies.

In addition to environmental effects, engineering components face complex fatigue conditions, such as asymmetric stresses, multiaxial stresses and so on[74,75]. Cyclic creep, or ratcheting, caused by cumulative plastic strain under asymmetrical loading with a non-zero mean stress, often leads to premature failure. Improving ratcheting resistance remains challenging due to the unavoidable cyclic softening and strain localization[76]. Recent work on gradient dislocation cell structures in 304 stainless steel has demonstrated superior ratcheting resistance under asymmetric and multiaxial loadings. This resistance stems from sustained microstructural refinement via a novel deformation-induced coherent martensitic transformation, forming stable hexagonal close-packed nanolayers that mitigate cyclic softening and suppress strain localization[76]. Such gradient dislocation architectures offer promising strategies for designing high-strength, ratcheting-resistant materials.

Future perspectives

Metal fatigue has persisted as a critical challenge in materials science for nearly two centuries, retaining its importance across a wide range of applications[37]. However, our fundamental understanding of metal fatigue remains incomplete, warranting investigation for two main reasons. The first reason is that extreme application environments, such as deep-space and ocean exploration, nuclear power plants and other harsh mechanical and environmental conditions, present fatigue challenges that differ from those encountered in laboratory settings. The second reason is that fatigue research must keep pace with the rapid innovation of material designs and technologies that introduce new fatigue issues. Next, we highlight some key challenges and opportunities for advancing fatigue-resistant metals and alloys.

Innovation in materials design and fabrication

The pursuit of more fatigue-resistant materials has spurred advancements in alloy design and manufacturing processes. Additive manufacturing, a cornerstone of digital transformation[77], enables near net-shape fabrication and complex compositional design, while its unique processing features—localized melting zones and rapid solidification—generate non-equilibrium cellular microstructures with chemical and physical inhomogeneities. These hierarchical features, unattainable by conventional methods, have shown promise in enhancing high-cycle fatigue resistance[24,78].

However, many fatigue-related parameters of additive manufacturing, critical for applications, remain poorly understood[77,79]. Defects from current printing processes, such as impurities and voids, often lead to early crack initiation and poor fatigue performance[80]. Complex interactions among anisotropic microstructure, residual stress, porosity, surface roughness, power quality and variable parameters further complicate the understanding of fatigue behaviour in additively manufactured metals[77].

An advance in alloy design is the development of multicomponent high-entropy alloys[81–83], particularly those based on the CrCoNi system. For example, NASA GRX-810, an oxide-dispersion-strengthened NiCoCr-based alloy designed for extreme environments[84], offers exceptional high-temperature creep resistance and cryogenic damage tolerance[84–86]. Some high-entropy alloys also demonstrate fatigue properties comparable to those of conventional structural materials (Fig. 1a,b). The vast compositional space of multicomponent alloys presents potential for designing next-generation fatigue-resistance materials for extreme applications[25]. However, systematic fatigue studies, especially on CrCoNi-based and refractory high-entropy alloys, remain limited.

The fatigue performance of high-entropy alloys and materials produced by additive manufacturing, particularly under complex service conditions such as multiaxial loading and environmental exposure, has become a research focus[75]. Leveraging these approaches to explore fatigue-resistant compositions offers a promising frontier for materials development and supports their application in critical loading-bearing structures.

Innovation in microstructure design and fabrication

The engineering of spatially heterogeneous structures, particularly through spatial gradient design, opens new avenues for cyclic strain delocalization[58]. The tunability of gradient structures—including their structural components and distribution characteristics—offers diverse pathways for tailoring fatigue performance. Nevertheless, the development of innovative microstructural designs aimed at achieving more sustainable, fatigue-resistant engineering solutions remains a challenge.

In addition to research on gradient structure fatigue, exploring the fatigue resistance of other emerging heterostructures, such as laminated, sandwiched, domain-dispersed and harmonic structures, represents an important direction. A key challenge lies in design and precise control of material structures across multiple length scales, as well as managing the degree and distribution of heterostructures, to achieve targeted fatigue performance. Integrating traditional alloying principles with heterostructured strategies offers broader opportunities for optimizing metal fatigue resistance. From a technical perspective, the development of cost-effective, efficient and scalable methods is essential for advancing the industrial application of these gradient and heterostructured materials.

Technical advancement for fatigue testing and characterization

To address fatigue challenges and ensure the long-term reliability of metallic materials, engineers must consider various factors when designing fatigue-resistant components, including material properties, complex loading conditions (such as asymmetric or multiaxial stresses, variable amplitude cycles, ultrahigh cycle fatigue), environment effects (such as oxidation, corrosion, hydrogen embrittlement) and temperature fluctuations from high to cryogenic levels[1]. Cyclic fatigue of metals presents practical challenges distinct from laboratory conditions. For instance, high-temperature fatigue, especially very-high-cycle fatigue in superalloys, is critical for improving gas turbine and aerospace performance, but remains difficult to accurately assess owing to complex fatigue–creep–oxidation interactions and the technical challenge for performing in situ atmosphere and high-frequency conditions[65,87–89]. Similarly, cryogenic fatigue, additionally affected by ductile-to-brittle transitions and phase transformations, poses challenges for applications in space, deep-sea exploration and liquefied natural gas storage[90,91].

The influence of multiple microstructural parameters, such as structural components, length scale, spatial distribution and gradient, on fatigue behaviours of heterostructured metals and alloys remains an underexplored area. To advance this field of metal fatigue, it is essential to strengthen the correlation between local characterization techniques (for example, atomic-resolution electron microscopy, site-specific focused ion beam nanofabrication, three- and four-dimensional transmission electron microscopy), strain mapping and global approaches (high-resolution digital image correlation, electron back-scatter diffraction combined with plasma focused ion beam)[38–40]. Both ex situ and in situ techniques, including synchrotron and neutron diffraction, are increasingly important. Quantifying the interplay among gradient structures, complicated compositions and phases, fatigue properties, the loading–unloading Bauschinger effect and cyclic mechanisms is essential for designing sustainable fatigue-resistant materials for critical structural components.

Fatigue mechanisms

Understanding the fatigue behaviour and underlying mechanisms of newly developed materials is crucial for preventing their premature failure, reducing maintenance costs and extending the service life of critical metallic structures. In-depth research on the fatigue damage resistance of heterogeneous compositions and microstructures remains limited. A comprehensive understanding of the evolution of heterogeneous microstructures under cyclic loading, encompassing the interactions between dislocations, boundaries and interfaces, as well as the origins and coupling of different mechanisms and inhomogeneous stress and strain evolutions across different length scales, is a critical area for future investigation.

In particular, the accumulation, interaction and stability of complex chemical and physical microstructures, along with unique interfacial behaviours and the resulting strain-delocalized cyclic response linked to strain gradients, play a key role in determining the effectiveness of non-alloying defect strategy. These microstructural attributes enable a level of fatigue resistance and robustness that conventional alloying approaches cannot achieve. Addressing these challenges requires more systematic in situ and ex situ microstructural characterizations and mechanical studies, supported by advanced multiscale modelling and theoretical analysis.

While some ‘low-hanging fruits’ in understanding fatigue mechanisms have been addressed, some long-standing challenges—such as the elemental vacancy activity resulting from dislocation interactions during cyclic loading[50]—remain unsolved and demand in-depth investigation. The intrinsic fatigue mechanisms of engineering alloys at both high and cryogenic temperatures are still poorly understood, yet critical for developing next-generation alloys with enhanced fatigue resistance for extreme environments. Progress in this area will rely on interdisciplinary collaboration and the integration of cutting-edge technologies.

Predictive modelling and data-driven approaches

The Basquin and Coffin–Manson equations have long served as the standard approaches for estimating and predicting the lifespan of materials under cyclic loading, yet they remain largely empirical. Incorporating advanced statistical and quantitative analysis into the study of conventional metal fatigue offers opportunities to improve fatigue prediction capabilities by leveraging advancement in modelling and mechanics. However, due to complex structural parameters and diverse fatigue conditions, the relationship between heterogeneous structures, fatigue properties and cyclic mechanisms remains insufficiently explored. This gap presents both opportunities and challenges for experimental investigations, modelling and simulations. Quantitative, multiscale modelling frameworks are needed to link structural features with fatigue resistance under varied conditions, particularly in harsh environments. Tools such as discrete dislocation dynamics show promise for capturing cyclic plasticity localization and informing future fatigue life prediction models[38].

Simulation- and data-driven approaches have greatly accelerated materials design and analysis[92,93]. Machine learning models, trained on experimental and simulation data, are increasingly used to uncover structure–fatigue property relationships, guiding material design. Integrating multiscale experiments with computational tools, machine learning and artificial intelligence will be essential for the future design of fatigue-resistant materials. Given the current lack of comprehensive theoretical models for fatigue in materials with heterogeneous structures and composition, data-driven approaches are expected to reshape fatigue research and accelerate the discovery of materials with tailored fatigue performance.

Concluding remarks

Fatigue in metals remains a critical area of research with profound implications for the safety, reliability and cost-effectiveness of engineering structures. Advancing our understanding of fatigue mechanisms, along with innovations in material and microstructural design, is essential for developing sustainable, high-performance solutions. Overcoming the challenges posed by fatigue, particularly in extreme environments, will require interdisciplinary collaboration and the integration of cutting-edge technologies. These efforts will be instrumental in reshaping the tailored design of fatigue-resistant materials for future engineering applications.

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Competing interests

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Additional information

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