Review

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Article

Reviewing the Integrated Design Approach for Augmenting Strength and Toughness at Macro and Microscale in Heterogeneous Metal Matrix Composites

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Abstract: In response to the growing demand for high-strength and high-toughness materials in industries like aerospace and automobiles, there is a need for metal matrix composites (MMCs) that can simultaneously enhance strength and toughness. This paper focuses on the design configurations of MMCs, which include both the configurations resulting from reinforcements and the inherent heterogeneity of the matrix itself. The mechanical properties of MMCs are influenced by factors such as reinforcement content, shape, size, and spatial distribution within the composite architecture. Among them, Aluminum matrix composites (AMCs) are particularly significant in aerospace, electronics, and electric vehicles due to their potential for weight reduction and enhanced performance. However, the challenge lies in the inverse relationship between strength and toughness, hindering the widespread utilization and large-scale development of MMCs. The design configuration of composites plays a critical role in achieving concurrent improvements in strength and toughness. This review explores the advantages of toughness, toughening mechanisms, reinforcement distribution characteristics, and structural parameters in the design of composite architectures. Drawing inspiration from biological composites like bone, the development of synthetic composites with homogeneous structural designs provides insights into attaining exceptional strength and toughness in lightweight engineering structures. Additionally, understanding fracture behavior and toughening mechanisms in heterogeneous nanostructures is vital for advancing the field of metal matrix composites. Summarily, the design of composite architectures holds tremendous potential for tailoring AMCs with outstanding strength and toughness, addressing the requirements of lightweight engineering structures in various industries.

Keywords: metal matrix composite; strengthening mechanisms; toughening mechanisms; heterogeneous architecture; energy dissipation

1. Introduction

As aerospace and automobile industries progress, the demand for materials with superior strength and toughness increases. However, strength and toughness, two crucial properties governing the performance and failure of metal components, often show an inverse relationship. This means that improving strength can compromise fracture toughness, posing an ongoing challenge for material scientists. One effective approach to enhance metal materials is the creation of composites [1,2], which involve incorporating high-performance particles into the metal matrix. These metal matrix composites (MMCs) offer notable improvements in specific strength, stiffness, wear resistance, and other desired properties [3–6]. Additionally, they possess advantageous characteristics like high conductivity, thermal conductivity, damping, wear resistance, and multi-functionality, making them valuable for future applications in metal structural materials [7–11].

In aerospace, electronics, and electric vehicle (EV) applications, the use of lightweight advanced metal, specifically metal matrix composites (MMCs), offers a strategic advantage due to their low weight, high strength, and high toughness. Particularly in aerospace manufacturing and spacecraft development, advanced aluminum matrix composites (AAMCs) are crucial foundational materials

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that enable cost-effective, multi-functional solutions while meeting goals for fuel efficiency and sustainability. This innovative approach in aerospace engineering provides reliable solutions to address present challenges and meet future design requirements. MMCs possess significant properties such as high structural efficiency, excellent wear resistance, and desirable thermal and electrical characteristics, making them valuable in various industries including automotive, rail, thermal management, aerospace, industrial, recreational, and infrastructure sectors [12]. By replacing conventional aluminum alloy materials with high strength and toughness aluminum matrix composites, structural weight can be reduced by approximately 20% to 25% while energy strength can increase by approximately 15% to 20% [2].

Aluminum matrix composites (AMCs) offer immense potential for aerospace applications that face extreme environmental conditions, including low temperatures, alternating temperatures, and extreme overloads. In industries like aerospace and electric vehicles, where reducing weight is crucial for minimizing fuel consumption and carbon emissions, AMCs provide an exciting solution. By significantly reducing weight while maintaining structural integrity, AMCs enable manufacturers to meet the challenge of weight reduction, fuel efficiency, reliability, and overall cost reduction. Over the next 5 to 10 years, Europe will prioritize deep space exploration and the development of new energy vehicles, particularly electric vehicles, aligning with the goals of the Paris climate agreement. Experts in AMC technology, such as those from Alvant [13], emphasize the potential of AAMCs to enhance the efficiency and performance of electric motors. Incorporating AAMCs can result in an impressive 40% reduction in rotor weight for axial flux electric motors, thereby increasing the potential power-to-inertia ratio of the rotor. Additionally, AAMCs exhibit excellent thermal resistance, capable of withstanding temperatures up to 300°C. This exceptional thermal resistance makes AMCs a more suitable material compared to other composites for various applications such as motors, batteries, energy recovery systems, fans, and flywheels [14]. However, the negative relationship between strength and toughness poses significant obstacles to fully exploiting the potential and broad adoption of MMCs, limiting their large-scale development and critical applications [10–12]. Therefore, it is imperative to overcome the trade-off between strength and toughness and achieve compatibility between high strength and toughness in innovative MMCs, which presents a crucial scientific challenge in the field of research. The design flexibility of composites is evident in three essential aspects: the selection of reinforcements, customization of interfaces, and configuration design [15].

Among these aspects, the design configuration stands out as the most intricate and challenging task in the design, fabrication, and processing of composites. From a microstructural perspective, the design configuration offers a promising approach to simultaneously enhance the strength and toughness of metal materials, provided that precise control over the structural elements is achieved. However, it is important to recognize that the strength-toughness relationship in metal matrix composites is affected by localized stress concentration, deformation mismatch, and the presence of high-density large-angle grain boundaries that promote micro-pore nucleation) [16,17]. Conventional approaches in metal matrix composites have focused on achieving homogenization and recombination of a single-phase, single-scale reinforcement and matrix. This approach aims to address issues such as inadequate matrix density, nano reinforcement agglomeration, structural damage, and boundary surface reactions [18,19]. The concept of "homogeneous composite" design inspired by biological composites has seen significant development, resulting in unique composite configurations [20–22].. Natural composites, like bone, exhibit exceptional strength, toughness, low weight, and self-healing capability due to their composite nature and hierarchical organization [21,22]. However, in synthetic materials, challenges remain in understanding the collaborative effects of structural factors on strength and toughness enhancement and developing effective processing methods for precise control over multi-level structures.

Currently, there is extensive research focused on the plastic deformation mechanism and strong plastic coordination of heterostructure metals. However, there is a relative lack of research concerning their fracture behavior and toughening mechanisms. This review paper aims to fill this gap by specifically examining heterogeneous nanostructures and providing an overview of their unique mechanisms for strengthening and toughening. In addition, the paper explores the potential of drawing inspiration from high-strength components found in biological systems, which are known for their exceptional toughness and intricate configurations. This approach holds promise for the development of advanced metal matrix composites that simultaneously enhance both strength and toughness in lightweight engineering structures. With composite architecture design playing a crucial role in cutting-edge materials research, the objective is to propose tailored architecture designs that exhibit exceptional strength and toughness. Consequently, this review paper investigates the advantages of toughness, toughening mechanisms, reinforcement distribution characteristics in architectural designs, and relevant structural parameters.

2. Strengthening and Toughening through Macro Heterogeneous Configuration of Reinforcement

To explore the concept of heterogeneity, this paper emphasizes the spatial distribution and size variations of reinforcements, considering the representative volume element (RVE) as the macro-scale structural unit [23]. In microstructurally inhomogeneous composites, there are distinct regions: a reinforcement lean region (representing the "soft" phase) and a reinforcement-rich region (representing the "hard/strong" phase) (Figure 1) [24]. It's important to note that different characteristics correspond to the reinforcement-rich or reinforcement-lean phases, rather than the inherent hardness of the ceramic reinforcement itself [24,25]. Achieving both strength and flexibility is a known challenge in material engineering, and typically, metal matrix composites involve a hard phase within a soft matrix. However, certain MMC design configurations, like TiC_p/Ti_6Al_4V composites with a network microstructure, have the harder phase as the continuous phase itself [24,26]. The presence of reinforcements not only supports the soft matrix but also hinders crack propagation by acting as obstacles. These composites exhibit heterogeneous microstructures with both soft and hard phases, influencing the final composite's strength and toughness characteristics at different length scales [27].

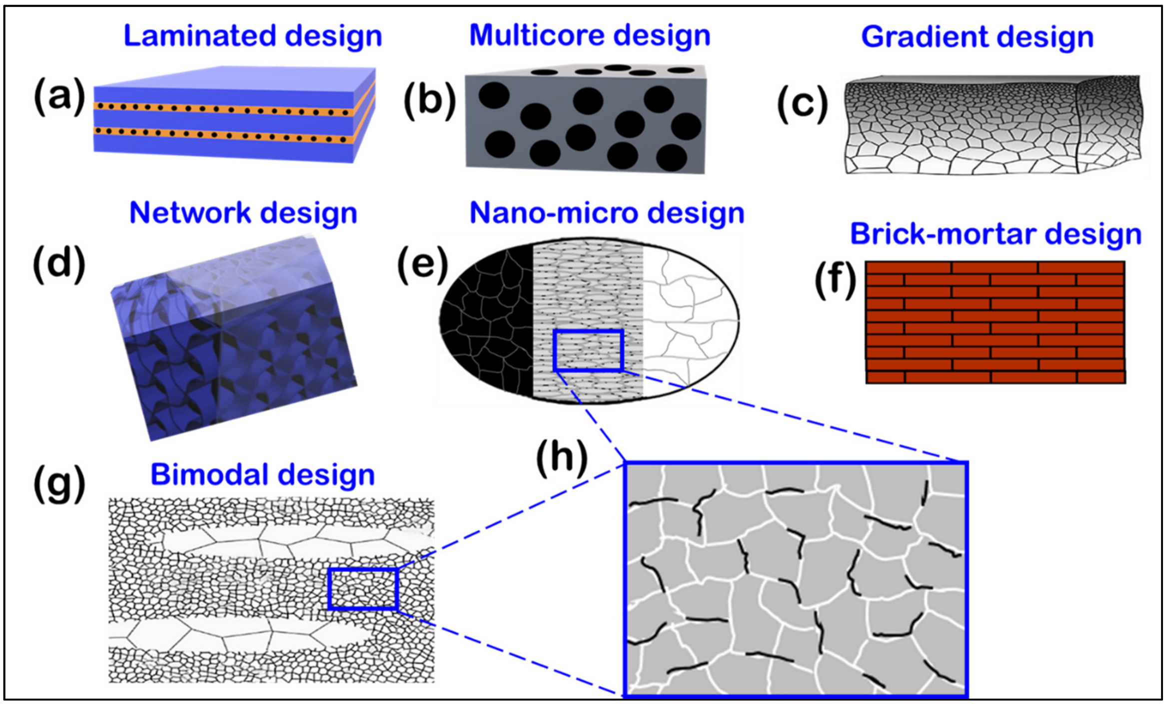

Figure 1. Illustration of the typical heterogeneous design configurations in metal matrix composites.

In this context, providing illustrative instances can enhance the understanding of this approach. Regarding the geometry of layers, multi-laminated structures demonstrate diverse macroscopic stress-strain behaviors under applied loads [28,29]. These structures effectively control the size of structural components at meso- and micro-scales, resulting in significant strength at the interface between the hard and soft phases. Furthermore, advancements in strengthening and toughness mechanisms, influenced by the interface-affected zone (IAZ) [30] or grain boundary-affected zone (GBAZ) [31–33], based on the theory of soft phase plasticity gradient [34,35], contribute to a deeper comprehension of the importance of grain boundary engineering. By modifying and developing structural components and employing mechanical models, the optimization of structural designs can be achieved.

The presence of heterogeneity in layered structures plays a vital role in improving toughness. While the orientation effects of the interface between the hard and soft phases are important, they mainly affect the normal direction and may lead to reduced hardness. To address this, some proposed structures increase the width of the soft layer to enhance workability and accommodate more dislocations [36–38]. Plastic strain primarily concentrates in the soft coarse-grain phase, with the hard ultrafine-grain (UFG) phase contributing less to strengthening and toughening [36]. However, such a structure may have limited failure due to premature necking in the soft layer. On the other hand, the multi-core configuration, also known as a concrete-like architecture [39], offers significant toughness and strengthening effects simultaneously by reducing the interface volume density between the soft and hard phases. Compared to layered composites, the designed composite with a multi-core configuration demonstrates higher fracture energy and prevents catastrophic failure under maximum load [40,41]. The gradient configuration, where the grain size increases from the nanoscale at the surface to coarse grain at the core, is a special design that mitigates stress concentration at the interface, resulting in improved toughness and strength [42–45]. Although progress has been made, further research is still required to optimize gradient sizes and explore new possibilities in this field.

The primary optimization approach for creating heterogeneous configurations involves the distribution of the reinforcement within the matrix phase, allowing control of the soft/hard phase interface strength and size optimization based on strain gradient plasticity theory. However, this approach has limitations as it neglects the interdependence between different reinforcements and structural components, such as grain size, reinforcement distribution, shape, and matrix crystal structure. If the configuration plan remains unchanged, local stress concentration can still lead to inhomogeneous plastic deformation, resulting in early necking and an inability to effectively overcome the strength/toughness trade-off. Conversely, reducing the size of the soft phase to a few microns can transform the multi-core configuration into an inverse nacre structure [46], where elongated and curled soft constituents are embedded within a matrix of hard constituents. This structure exhibits increased tensile elongation and strength, with the soft phase's strain-hardening capability compensating for the strain softening of the hard phase caused by microcrack formation. The dispersed soft phase stores plastic deformability until neighboring hard phases develop microcracks [41], which are then blunted and inhibited from propagating by the full plastic deformation and hardening of the soft phase at the crack tip[47]. The superior comprehensive strengthening-toughening effect arises from the tailored hierarchical structure, promoting stable microcrack-multiplication through sufficient strain hardening and preventing significant reduction in post-ultimate tensile strength.

3. Strengthening and Toughening of Microheterogeneous Configurations of Reinforcements

A design configuration comprises microelements that interact and form mesoscopic objects, acting as building blocks within the RVE [48]. When discussing heterogeneous configurations of reinforcements, we refer to the relationship between micro and nano-scale reinforcements and their distribution, size, shape, and other structural parameters in relation to the matrix material. The terms network, micro-nano, and micro-nano hybrid architectures are used to describe the design scale and configuration, all sharing the characteristic of evenly distributed reinforcements on macro and micro/nano scales within a specific engineered structure. AMMCs exemplify this concept by exhibiting improved grain boundary efficiency compared to base materials or those with crystalline particles. This enhancement is attributed to the presence of a three-dimensional network of closed alumina cells at the microscale, filled with elastoplastic aluminum. This network effectively hinders restoration mechanisms across grain boundaries and grain boundary sliding during hot deformation, resulting in a highly stable UFG structure with superior thermal and strain stability [49–51]. Such macro heterogeneous designs hold great potential for developing materials with desirable properties suitable for load-bearing structural applications, particularly at high temperatures.

Previous studies [52–54] have shown a shift in the design approach for network configurations, moving from continuous networks of reinforcements to quasi-discontinuous and quasi-continuous networks. The original design of the ($Al_3Zr+Al_2O_3$np)/2024Al continuous network composite revealed concentrated and agglomerated reinforcement areas along the matrix's grain boundaries, resulting in significant stress concentration and a limited balance between strength and toughness. Attempts to adjust sintering temperature, pressure, and other process parameters did not yield satisfactory strength and toughness balance [55]. On the other hand, configurations featuring quasi-continuous or continuous networks of reinforcements, such as SiC/Al composites with a 3D quasi-skeleton (interpenetrating network structure), have demonstrated notable improvements in thermophysical properties. The geometry of the SiC reinforcement significantly influences these properties, and the co-continuous structure of SiC reinforcement and the Al matrix in 3D-SiC/Al composites has proven particularly advantageous [52]. These configurations not only exhibit excellent homogeneity but also demonstrate enhanced mechanical and elastic properties due to their unique structure and strong interfacial bonding between the matrix phase and the reinforcing phase [53,54].

Compared to traditional composites that utilize particles or fibers as reinforcements, composites with an interpenetrating phase network exhibit improved toughness and isotropic microstructures. In MMCs with a 3D quasi-continuous network structure, the interfacial area between the continuous ceramic and metal phases is smaller, resulting in lower interfacial thermal resistance compared to particle-reinforced MMCs with the same ceramic volume fraction [52]. By strategically distributing reinforcements within a network or quasi-continuous skeleton, the strength and toughness of titanium matrix composites can be simultaneously enhanced at room temperature. Furthermore, incorporating a discontinuous three-dimensional graphene network into copper-based composites enhances their ability to accommodate geometric dislocations, leading to improved mechanical properties such as increased elastic modulus, yield strength, tensile strength, elongation at fracture, and fracture toughness [56]. This type of network configuration ensures a uniform dispersion of reinforcement throughout the matrix, ultimately enhancing the strength and toughness properties of the metallic composite. Additionally, optimizing structural parameters such as size, shape, and reinforcement distribution characteristics is expected to further enhance the strength and toughness properties.

The nano-micron hybrid configuration is an effective design that combines two different sizes of reinforcements to synergistically enhance both strength and toughness during loading. Larger particles can bear significant loads and accumulate strain energy, triggering recrystallization in the surrounding metal matrix [17,57–59] . On the other hand, smaller nanoparticles reduce stress concentration in GBAZs and IAZs around the larger particles, delaying phenomena like recrystallization and grain growth (Figure 2) [3,60–63]. Achieving a homogeneous distribution of reinforcements in two different scales is challenging in traditional manufacturing processes, particularly for nanocarbon materials like carbon nanotubes and graphene, limiting the attainment of desired toughness and plasticity in nano/micron hybrid configurations [64–68].

In order to identify a suitable fabrication technique, step-by-step powder metallurgy, also known as powder assembly, has emerged as one of the most effective and practical methods for achieving the essential structural parameters and harnessing the synergetic effects of reinforcements with different size scales in composites. Employing this approach, the (B_4Cp+Al_2O_3np)/Al micro-nano hybrid composite has been successfully produced, exhibiting an elongation-to-fracture of approximately 8.9%. This value surpasses the elongation-to-fracture of 4% observed in B_4C/Al composites reinforced solely by micron-scale reinforcements. The presence of submicron-sized Al_2O_3 nanoparticles within the aluminum grains, forming Orowan loops in the grain interiors, significantly contributes to the hardness and facilitates uniform plastic deformation [43]. Furthermore, the adoption of a reinforcing design configuration leads to enhanced fatigue and strength properties in bimodal-sized Al_2O_3/Al nanocomposites, which incorporate both micro-sized and nano-sized Al_2O_3 particles. The uniform presence of nano-sized alumina within the grain interior restricts dislocation mobility, while the micro-sized alumina at the grain boundaries limits grain boundary migration [17].

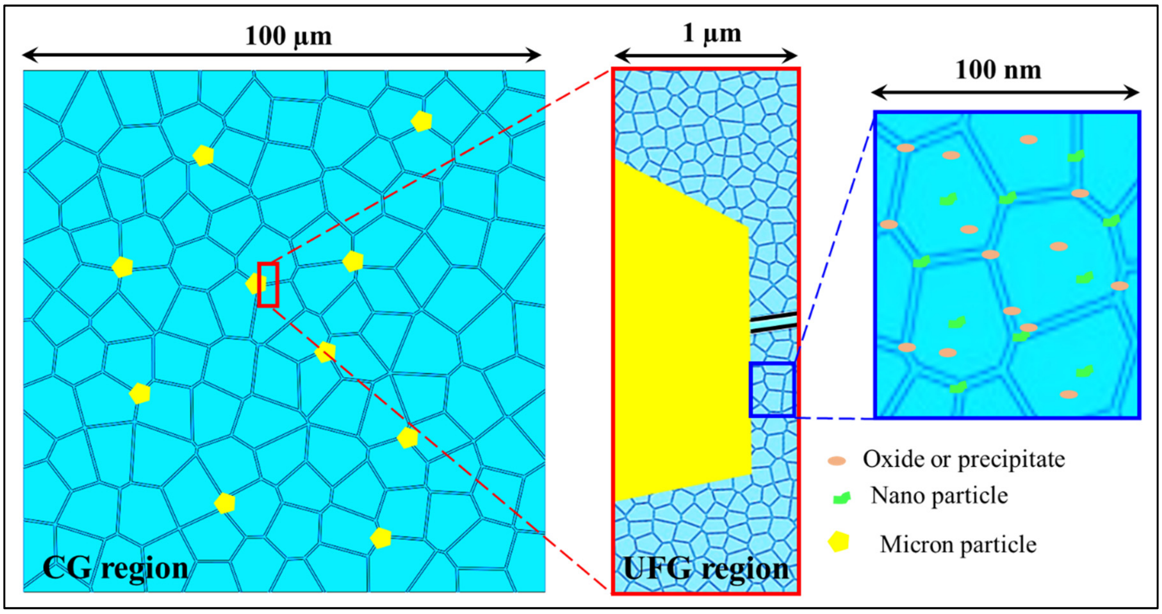

Figure 2. Schematic of the micro-nano hybrid architecture; Size-dependent design and cooperative dispersion of micron particles and nanoparticles in the micro-nano hybrid configuration.

The incorporation of nanoparticles as reinforcements within the matrix grains surrounding micron-sized reinforcements offers a significant enhancement in both toughness and tensile strength. In specific cases, the addition of sub-micron Al_2O_3 particles in nano/micron hybrid composites, such as (Al_2O_3p+AlN-np)/Al, facilitates the dispersion of AlN nanoparticles. The presence of submicron reinforcements activates a portion of the matrix grains, leading to recrystallization and reorganization of stored dislocations, resulting in simultaneous increases in strength and toughness [51,69,70]. However, achieving a uniform distribution of high-modulus and high-strength nanocarbon reinforcements, like CNTs and graphene, within composite materials remains a challenge for the development of advanced MMCs. The adverse effects, such as side reactions and metal carbide formation at interfaces, can disrupt the structural integrity of CNTs or graphene due to excessive ball milling energy during the initial manufacturing process. Therefore, minimizing energy input is proposed as a solution [43]. Moreover, the accumulation of nanocarbon reinforcements significantly affects the plastic behavior of the resulting composite. For example, in a (SiCp+CNT)/6061Al nano-micron hybrid composite fabricated through mechanical milling, where CNTs are grown in situ on the micron surface of SiC particles, significant increases in Young's modulus, yield strength, tensile strength, and elongation at failure are observed [44,45]. Utilizing a pre-dispersion process, such as high-shear pre-dispersion, has also proven effective in pre-dispersing nanocarbon on the surface of flaky-shaped Al powder and providing improved protection in subsequent mechanical powder processes [64,71]. A well-coordinated CNT dispersion, structural integrity, and interfacial bonding in an as-fabricated 1.5 wt%CNT/6061Al composite demonstrate enhanced tensile toughness. These findings emphasize the importance of structural designs that ensure reasonable distribution of multi-size and multi-phase reinforcements while considering optimal conditions to achieve desired composite properties. Excessive volume fraction of reinforcements within the metal matrix should be avoided, as it can lead to stress concentration at interfaces and in the GBAZ, resulting in poor mechanical behavior in terms of strength and toughness. In summary, the shape and size of reinforcements play a crucial role in achieving high strength and toughness in composite materials. It's worth noting that the toughness of composite materials exhibits a turning point or reversal at a certain stage.

Inspired by the micro-nano brick structure found in nacre (mother of pearl) [21], efforts have been undertaken to develop a similar configuration in layered composites. This configuration involves the distribution of reinforcements with varying size scales, shapes, and distribution within the matrix. Similar to the brick-and-mortar arrangement, brick-shaped mineral platelets at the microscale are embedded in a matrix of nano-scale material. The utilization of flake powder metallurgy technology has played a crucial role in achieving precise control over the configuration parameters in layered composites [66,72]. By producing platelets in two dimensions, this approach ensures better geometric compatibility, leading to a more uniform distribution of reinforcements. Furthermore, the elongated grains with an increased aspect ratio (width in the nanometer range and length in the micrometer range) enable the storage of dislocations. This facilitates the intentional placement of in-situ Al2O3 nanoparticles, CNTs, graphene plates, and other reinforcements at the grain boundaries of the elongated grains. As a result, a high density of geometrically necessary dislocations (GNDs) is formed near the grain boundaries and interfacial zones, compensating for the loss of strain hardening caused by ultra-fine grains [73,74].

Various techniques have been employed to enhance the mechanical entanglement and load transfer effect at interfaces in composite materials. These methods include combining powder metallurgy (PM) with conventional rolling [3,65], electrophoretic deposition of CNTs on metal foil [75], constructing biomimetic mineral bridges, and in-situ reinforcement growth [76], among others. By improving the interfacial bonding and structural quality of the reinforcement, these techniques require more energy for crack propagation, resulting in a significant increase in toughness.

The geometric compatibility between two-dimensional graphene plates and flake-shaped building blocks formed in the flake PM process makes graphene an ideal reinforcement for biomimetic brick matrix structures. For example, in the GNS/Al micro-nano brick composite, the geometric compatibility of graphene plates with flake-shaped platelets prevents the annihilation of dislocations at the grain boundaries [77,78]. This composite demonstrates an increase in tensile strength from 201 MPa to 302 MPa, while maintaining a similar level of elongation to fracture.

A recent design approach has been explored for high-performance Ti2AlC/TiAl composites with a micro-nano laminated configuration. This design exhibits a favorable combination of compressive strength (1807 MPa) and ductility (25.5%) at room temperature [79]. The composite consists of micro-laminated Ti2AlC, micro-nano γ-TiAl/α2-Ti$_3$Al lamellar colonies, and nano-laminated Ti2AlC. These structural characteristics contribute to the enhanced strength of the Ti$_2$AlC/TiAl composite through load transfer strengthening and Orowan strengthening effects commonly observed in metal matrix composites. Additionally, this design configuration effectively improves the ductility and toughness of the Ti$_2$AlC/TiAl composite through multiple plastic deformation mechanisms [79]. The configuration of a design, including the size and shape of its components like grains and particles that provide reinforcement, plays a critical role in the ability to store dislocations and the likelihood of defects forming within the structure. The response to high strain rates is affected by the constraints imposed by the reinforcement's geometry [45,66,80]. Furthermore, the interplay between intrinsic mechanisms (related to plasticity) and extrinsic mechanisms (related to shielding) for enhancing toughness is highly influenced by the design configuration [81–83]. Intrinsic mechanisms primarily operate at small scales (nano or micrometer) ahead of the crack tip, strengthening a material's inherent resistance to damage and consequently increasing both crack initiation and propagation toughness. Conversely, extrinsic mechanisms create a shielding effect at larger length scales, mostly behind the crack tip, affecting only the toughness during crack propagation [84]. Essentially, intrinsic toughening relies on plasticity to enhance a material's resistance to damage, resulting in improved crack initiation and propagation toughness. On the other hand, extrinsic toughening reduces local stress and strain at the crack tip and is only effective in the presence of a crack, influencing crack propagation toughness. In this context, the combination of multi-scale external toughening mechanisms [31,75,85] induced by reinforcements and the matrix can significantly contribute to increased work hardening and the display of exceptional strength and toughness.

In configurations featuring microscale heterogeneity of reinforcements, incorporating nanosized reinforcements alongside submicron and micron reinforcements leads to improvements in strength and toughness across various size scales, ultimately enhancing the balance between stability and toughness. The utilization of nanoscale reinforcements in future advanced composites is considered crucial, as indicated by numerous studies [86,87]. For instance, a boron carbide (sn-B_4C)/Al composite with spatial arrays of sn-B_4C demonstrated a significant increase of 26% in tensile strength and 30% in toughness. This enhancement can be attributed to the presence of fiber-like nanoparticle-rich (NPR) zones, acting as "hard" fiber-like units, effectively sustaining tensile loading and enhancing the strengthening efficiency of sn-B_4C. Furthermore, the arrangement of NPR zones, surrounded by nanoparticle-free (NPF) zones as the softer phase, contributes to improved strength with minimal loss in ductility [86–88].

The reinforced design configuration, particularly the fiber-like distribution of reinforcements, introduces additional microstructural strengthening through dislocation strengthening and the activation of Orowan mechanisms. The presence of spherical nanoparticles within the NPR zones immobilizes more dislocations, leading to a significant disparity in hardness values between the NPR and NPF zones. This disparity enables stress transfer from the "soft" NPF zones to the "hard" NPR zones, resulting in the extraction of some fiber-like NPR zones at the fracture surface during tensile loading. However, challenges persist in achieving uniform distribution and limited work hardening in ultrafine grains. Controlling the spatial distribution of reinforcing particles at the micro and mesoscale to engineer distinctive microstructural configurations has emerged as an innovative approach to overcome existing trade-offs in material properties [32,89,90].

It is important to note that both macro- and micro-scale configurations of reinforcements significantly influence the balance between toughness and strength in metal composites. However, achieving a satisfactory spatial dispersion of reinforcements requires careful consideration. For example, achieving a uniform intragranular dispersion of CNTs in an aluminum matrix necessitates specific conditions related to time, energy, external applied stress, and thermal activation [91,92]. Moreover, challenges remain in overcoming the strength-toughness trade-off, emphasizing the need for further extensive research in the field of strengthening and toughness mechanisms.

4. Strengthening and Toughening the Matrix through Intrinsic Mechanisms

The enhancement of toughness and strength in metal matrix composites depends not only on the uneven distribution of multiple reinforcing phases at different length scales but also on the structural parameters of the design configuration. Heterogeneous structures consist of diverse microstructural components combined at interfaces with strong bonding. The incorporation of alternating strength and toughness in the design configuration of heterogeneous metal matrix composites effectively improves their toughness, and the specific toughening mechanisms are influenced by factors such as crack orientation, interface strength, and microstructural characteristics of the components. These structures exhibit notable variations in mechanical properties on either side of the interface due to the presence of multiple heterostructures. Typically, the greater the difference in mechanical properties, such as hardness and strength, between the components, the more significant the strengthening effect of layered materials. The strengthening effect in heterostructured metals is attributed to the incompatibility of deformation between the constituent units, leading to a prominent strain gradient near the soft/hard interface. However, certain structural features, such as the ultrafine grain size of the matrix, can restrict the ability to undergo work hardening, consequently affecting the improvement of strength, toughness, and plasticity in the resulting configuration.

In conventional MMCs with grain sizes ranging from a few microns to several hundreds of microns, both plasticity and toughness typically increase simultaneously. However, in specially designed composites consisting of ultrafine grains, there is a trade-off where toughness and plasticity decrease while strength increases. This trade-off is attributed to the strengthening contribution of grain boundaries and interfaces, which is achieved through effective grain refinement processes during powder metallurgy preparation [93], Zener pinning effects [61,94–96], and other factors that lead to grain refinement to ultrafine or even nano-scale sizes. Creating conditions for plastic deformation, such as twinning or introducing atomic arrangement defects under low temperature and high stress conditions, is comparatively challenging and nearly impossible when compared to other deformation techniques [93]. The presence of low-energy coherent twin boundaries effectively impedes the movement of dislocations, thereby strengthening MMCs while still maintaining acceptable levels of plasticity and work hardening [97]. This advantage applies not only to uniformly structured nano twin metals [98,99] but also to the strengthening and toughening of heterogeneous structures in MMCs [100].

It is important to acknowledge that stress-induced transformation through plastic deformation is only viable in specific composites with particular compositional and microstructural conditions [101]. Various mechanisms, such as grain rotation, grain boundary migration, grain boundary sliding, and dislocation climb, influence the work hardening ability at both room temperature and high temperatures, thereby playing significant roles in determining the strength and toughness properties [102–104]. However, the presence of these mechanisms often weakens the intragranular work hardening ability, resulting in reduced toughness and plasticity. As a result, achieving uniform elongation with minimal loss in strength properties requires compensating for the decline in work hardening ability observed in ultrafine or nanoscale grains.

Recent studies [83-81-82-83], have revealed that two critical factors, namely intrinsic heterogeneous deformation-induced (HDI) hardening and HDI stress, have notable impacts on enhancing the strength-toughness relationship in metal matrix composites (MMCs) reinforced with nanoparticles. According to this theory, grains with multiple scales exhibit varying plastic deformability, enabling the activation of HDI. This leads to strain partitioning, resulting in back stress hardening in the softer zones and forward stresses in the harder zones, thereby contributing to HDI hardening. In other words, during the plastic deformation of heterostructured materials, the heterogeneous zones deform non-uniformly, which is believed to be responsible for the strengthening and additional strain hardening observed in heterogeneous materials [105,106]. This mechanism facilitates an optimal combination of strength and toughness properties.

HDI hardening arises from the interaction between the hard and soft zones, creating an elastic-plastic situation at the microscale during deformation. Within the soft domain, GNDs are impeded and accumulate at domain boundaries, leading to the development of long-range internal stress known as back stress. This back stress is believed to contribute to the enhanced strength of heterostructured materials [107]. On the other hand, in the hard zones, stress concentrations occur at the zone boundaries due to the accumulation of GNDs, generating forward stress with magnitudes several times higher than the applied stress [106]. The accumulation of dislocations in the soft phase induces forward stress in the hard phase, establishing a balance in mechanical properties. The specific stress states that emerge at the interface between the hard and soft zones, influenced by the mechanical behavior of the hard phase relative to the soft phase, significantly impact the material's toughness and strength. The back stress and forward stress are coupled at the domain (or grain) boundary and act in opposing directions. Importantly, the forward stress is induced by the back stress, and it can be logically deduced that the exceptional combination of strength and ductility observed in heterogeneous MMCs with a well-designed configuration is attributed to the back stress, aligning with the assumptions made in [105,106,108,109].

The ongoing research in the field of heterogeneous MMCs focuses on investigating internal factors associated with design configurations and their impact on material properties [110]. The intrinsic design of the matrix in heterogeneous MMCs is influenced by factors such as grain shape, size, and interface bonding, which play significant roles in work hardening, crack initiation and propagation, as well as the resulting strength and toughness behavior. The inclusion of nano-sized reinforcements at grain boundaries, known as the Zener pinning effect, offers effective control over grain size compared to other factors like alloy solutes, dislocations, and precipitates [95,96,111]. As a result, it is anticipated that MMCs can provide greater freedom in structural design and mechanical property control.

Early attempts at bimodal designs in metal composites relied on a trial-and-error approach, lacking a comprehensive understanding of the mechanisms behind strengthening and toughness, leading to misconceptions about fracture mechanics in such configurations. However, by optimizing the input energy in processes like ball milling [51,112], friction stir processing [61,113], or incorporating

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reinforcing nanoparticles, it becomes possible to regulate the grain size of the matrix and create a bimodal grain structure, thereby enhancing the toughness and strength properties of the composite. A proper allocation of tasks between reinforcement particles and the matrix can effectively generate bimodal-sized metal matrix composites by introducing bimodal-sized SiC particles [114]. The presence of multiscale reinforcement significantly influences the development of the bimodal structure, where regions without coarse SiC particles represent the coarse-grain regions, and grain sizes around nano SiC particle bands represent the fine-grain regions. This approach achieves a favorable balance between strength and toughness, benefiting from grain refinement, Orowan strengthening, coefficient of thermal expansion (CTE) strengthening, uniform distribution of nano SiC particles, and the presence of coarse grains [37,114]. While the achieved tensile plasticity may not be exceptionally high [62,114], it has been reported that the back stress strengthening effect in the elongated coarse-grained region surpasses that in the spherical coarse-grained region [115]. However, further investigation is still required to quantitatively optimize the relationship between the coarse-grained region and the submicron-sized microcrystalline region [116,117].

Currently, the focus of grain size optimization in the design concept revolves around determining the size of the IAZ, which refers to the zone with a strain gradient [30]. This determination is based on the theory of strain gradient plasticity [26] and the intrinsic engineering toughness derived from linear elastic fracture mechanics. In heterogeneous MMCs, the characteristic IAZ is formed near interfaces due to the density gradient of GNDs. When plastic deformation occurs, dislocations emitted from sources at the interface create the IAZ, which typically has a length scale on the order of several micrometers. While the width of the IAZ remains relatively constant with increasing tensile strain, the strain intensity within the IAZ increases, resulting in a higher strain gradient and work hardening through back-stress effects [30]. The optimal spacing of the IAZ plays a crucial role in achieving a high level of intrinsic strength-toughness, as illustrated in Figure 3 and demonstrated in studies on composites such as CNT/Al [36,65,118]. It has been found that in a heterogeneous configuration of matrix grains, the best combination of toughness and tensile strength is attained when the width of the coarse grain region is reduced to approximately twice the width of the IAZ [60]. Another approach is to have the diameter of the spherical coarse grain region equal to the plastic zone at the tip of the nearest crack [61,62]. In a bimodal grain structure with numerous interfaces between UFG and coarse-grained regions, a high density of GNDs is accumulated at the heterogeneous interfaces during deformation due to their incompatibility in deformation [30]. This accumulation of GNDs gives rise to the formation of the IAZ, effectively enhancing work hardening through multiple dislocation-mediated mechanisms. The volume percentage of these interfaces significantly influences the work hardening induced by heterogeneous deformation at the soft/hard phase interface areas.

Moreover, the combination of flexibility, toughness, and high strength can be attained through a trimodal grain configuration in powder metallurgy-produced MMCs. This configuration involves the distribution of fine grains between coarse and ultrafine grains, resulting in a trimodal grain structure. Such a configuration helps reduce stress concentration and inhibit strain localization within the microstructure [36,119]. For instance, in CNT/2024Al composites, the trimodal grain configuration exhibited significantly higher yield strength (561 MPa), tensile strength (723 MPa), and uniform elongation (6.7%) compared to the bimodal grain configuration with a yield strength of 532 MPa, tensile strength of 625 MPa, and uniform elongation of 3.8% [120]. The presence of multiscale features in the trimodal grain structures effectively contributes to the exceptional strength-toughness balance observed in trimodal MMCs.

It is worth noting that microstructures with gradient designs hold promise for stability and toughness enhancement [85]. However, achieving optimal mechanical properties through gradient configurations in MMCs remains challenging. Conventional processing techniques struggle to precisely control structural gradients across a range from nanoscale to macroscale, leading to limitations in achievable gradients. Unlike alloys, achieving precise grain gradients similar to those in alloys is difficult due to technical issues in preparing gradient configurations and the pinning effect of reinforcements on grain boundaries. Deformation at the scale of structural gradients differs fundamentally from deformation in conventional metallic materials [85]. This type of deformation exhibits unique dislocation behavior, interface-related phenomena, and interactions between GNDs and interfaces. Furthermore, the inhomogeneous deformation of gradient nanostructures results in the development of a long-range HDI stress field [107,121].

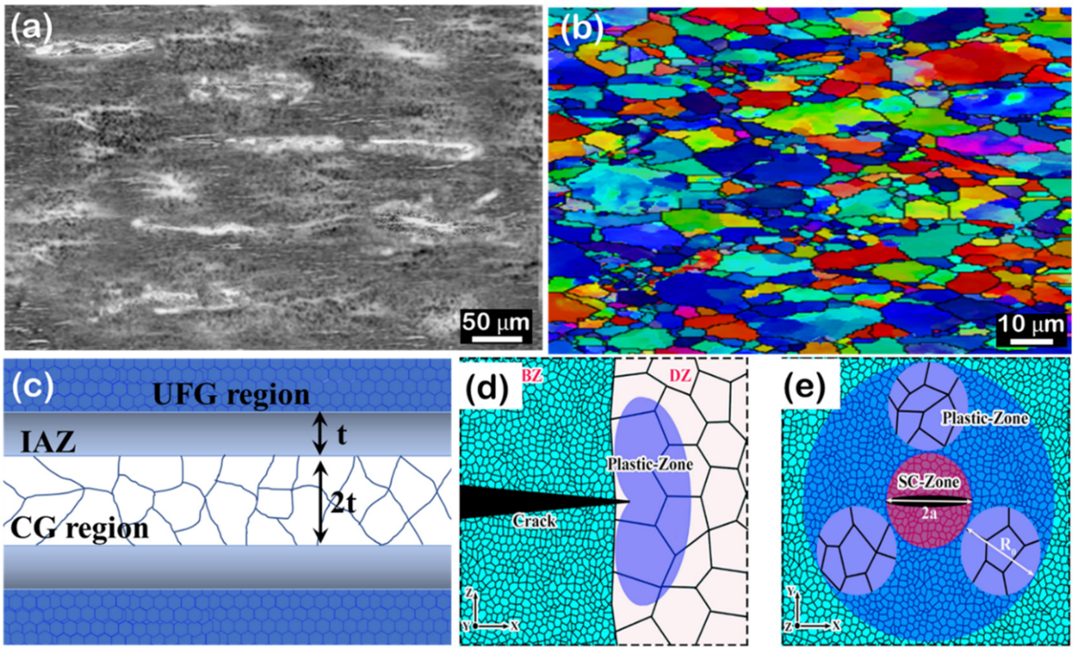

Figure 3. (a) OM images of heterogeneous configuration of Al-Mg/1.5 wt.% CNTs in the as extruded condition [36] (b) IPF map showing the grain structure of Al-Mg/1.5 wt.% CNTs, [36] (c) Schematic of interface affected zone (IAZ) in the trimodal configuration in Al–Mg/CNTs composites, (d,e) Schematic of toughening mechanism in heterogeneous materials [122].

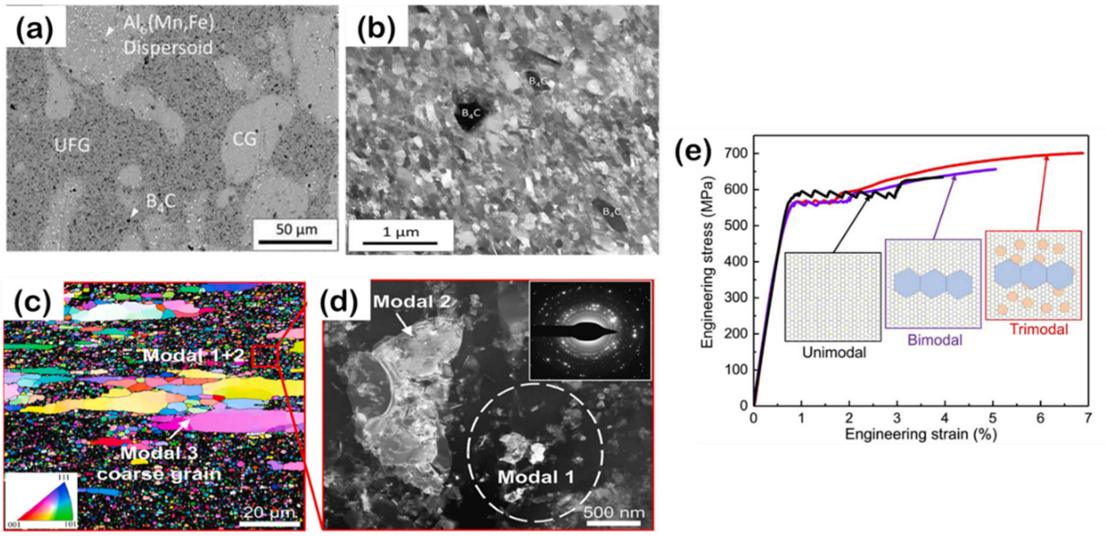

Figure 4. (a) Enlarged view of the microstructure showing UFG matrix with B4C(dark particles) and CG regions with Al6(Mn,Fe) dispersoids (bright particles) [123], (b) STEM annular dark field image of the UFG matrix, [123] (c) IPF map showing three-modal grain structures [115]; (d) TEM dark-field image of modal 1 and 2 grain structures, insert is the corresponding SAED pattern [115], (e) Representative engineering stress-strain curves of CNT/Al-Cu-Mg composites with different grain structures [120].

Currently, the primary focus of research lies in controlling structural parameters, although their influence on mechanical properties remains unclear. For example, while the presence of "soft" layers is believed to enhance plastic deformation capability, an excessive number of such layers can compromise the strength of the composites [124]. In the case of a bimodal design configuration, narrow coarse grain bands offer greater advantages in terms of toughening and strengthening compared to wider or ultra-narrow coarse grain bands, mainly due to their effective microcrack blunting effect [125]. In heterogeneous MMCs design configurations, cracks tend to initiate in brittle zones (BZs) rich in reinforcements due to their limited ductility. However, as these microcracks propagate into ductile zones (DZs) free of reinforcements, plastic deformation occurs in the DZs, effectively blunting the cracks [122]. This elastic-plastic deformation behavior near the microcrack tip, as per linear-elastic fracture mechanics, aids in blunting the microcrack, preventing further propagation, and achieving a favorable balance between strength and toughness. Furthermore, the strategies for adapting structural parameters and optimizing the interaction between structural components, such as reinforcements, matrix grains, and affected regions, are not yet well-documented and require comprehensive further research.

It is important to note that the design resulting from the combination of two-scale reinforcement and a bimodal-sized matrix structure is not restricted to dual matrix micro/nano hybrid structures. Theoretically, any reinforcement configuration can be related to the matrix configuration. In this context, dual gradient configurations have been developed within the framework of composite metal matrices [126,127], warranting further investigation. The gradient distribution of reinforcement particles within the metallic matrix enhances the material's mechanical properties and effectively hinders the localized rapid growth of surface nanocrystals. This provides an effective approach for inhibiting grain growth during the preparation of advanced MMCs using powder metallurgy techniques [126]. Additionally, a multi-level gradient structure in a B_4C/Al composite, incorporating reinforcements, dislocations, and precipitates, has demonstrated high strength of approximately 1291 MPa with no significant interlayer cracks or microstructure degradation after deformation, thus contributing to high toughness [127]. In general, in order to enhance the design concept for optimizing composite configurations and determining a suitable process path, it is crucial to identify and specify the strengthening and toughness mechanisms involved in developing configuration designs, particularly those primarily achieved through powder metallurgy techniques.

5. Designing and fabricating composite configurations based on energy dissipation

The ability of a design configuration to undergo limited deformation is crucial in enhancing fracture toughness as it allows for the localized dissipation of high stored energy that would otherwise reduce the material's damage tolerance [128]. The effectiveness of energy dissipation strongly depends on the specific design configurations used [129]. Although synthetic composite design configurations, particularly in metal-based composites, have made some progress in addressing toughness and strength challenges, most advancements have been achieved through experimental research and trial-and-error methods [130]. Existing mechanical theories are insufficient in fully explaining the complex relationships between structural components, forces, and various factors present in different configurations. Further investigation into the relationships between properties and components in such configured composites reveals issues with phase design criteria and uncertain toughness mechanisms. It is important to note that simply mimicking natural biomaterial components and recognizing their exceptional properties without a detailed understanding of the underlying reasons and mechanisms will not lead to the same level of performance. Therefore, there is an urgent need for innovative research to uncover the intrinsic scientific principles that simultaneously enhance strength and toughness. This research should focus on developing theories and technologies for new configuration designs in advanced metal matrix composites, providing comprehensive answers to the “how and why” behind the emergence of superior properties, particularly high strength and toughness.

Fracture mechanics principles dictate that the mechanical behavior of materials involves the dissipation of external energy applied to their structures. Understanding this concept has revealed that engineered design configurations can significantly improve mechanical behavior and increase the toughness of metallic materials and metal matrix composites by utilizing various energy loss

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mechanisms [131,132]. The customization of design configurations in heterogeneous metal matrix composites has a profound impact on crack propagation and deflection, leading to effective energy dissipation, which enhances composite toughness [133,134]. Taking inspiration from biological systems, renowned for their exceptional strength and toughness, can be a fundamental approach to optimize composite material configuration plans and achieve maximum strength and toughness [135]. In terms of energy dissipation, the development of energy dissipation theory should focus on two aspects to enhance the optimization of composite configurations' design strategy.

The first aspect involves preventing cracking and maximizing the dissipation of static plastic deformation energy. This is achieved by designing the composite interface and overall configuration in a way that enables multiple energy dissipation mechanisms with overlapping deformation processes. By allowing all components of the composite to participate in the energy dissipation process, local strain concentration is effectively avoided, and crack nucleation is inhibited. Through engineering the structural parameters of the design configuration, energy dissipation is particularly enhanced at preferred void nucleation sites, thereby reducing the capability of void formation [136]. The second aspect focuses on restricting crack propagation to maximize energy dissipation at the crack tip. The design of composite configurations occurs at micro and nano scales and incorporates heterostructures such as non-uniform interfaces and multi-scale reinforcements. These factors have a significant impact on the crack tip and its path of propagation, activating toughening mechanisms such as crack tip shielding, crack deflection, and bridging. In contrast, in a configured design in MMCs, crack propagation faces additional energy consumption, which makes expansion challenging or even prevents it altogether. However, when pursuing configurational composite preparation with the goal of maximizing energy dissipation, it is crucial to fully consider the action mechanism of the microstructure, including the effects of defects (such as interfaces, dislocations, cracks, local plastic deformation zones, etc.) within the material system on deformation behavior and energy dissipation. This requires precise regulation of the fine structure of composite configurations at both cross-scale and local levels, ensuring that the composite configuration meets the requirements of mechanical performance and energy consumption. However, due to the complexity of the composite system, achieving controlled fabrication of multi-phase and multi-scale configurations faces technical challenges primarily related to “shape control” and “controllability.”

The first challenge pertains to the differences in size, density, morphology, and surface/interface properties between the multiphase and multi-scale reinforcement phases and the matrix. These discrepancies result in inconsistent dispersion conditions and make it difficult to achieve effective dispersion of the components using the same preparation process. Consequently, the production of controlled composite configurations is hindered. Current technologies rely on applying sufficient energy to the composite system to promote uniform dispersion, employing methods like ultrasonic stirring, high-energy ball milling, friction stir processing [137–140], or laser remelting [141,142]. However, it's important to note that additive manufacturing processes, which are used to produce design configurations, face limitations in widespread application due to factors such as high costs, limited applicability in manufacturing large structures and for mass production, inferior and anisotropic mechanical properties, and constraints in feedstock materials [142,143]. Although these top-down dispersion and composite methods can achieve satisfactory dispersion effects, they fail to achieve orderly assembly between micro- and nano-scale reinforcing phases, and the matrix often becomes metastable. Consequently, subsequent heat treatment may lead to structural disorder and transformation. Hence, it is crucial to develop new principles and approaches for preparation technologies that address the challenges associated with synergistic dispersion of multi-phase and multi-scale reinforcements and the synergistic regulation of the matrix structure. The ultimate goal is to achieve “shape control” in configurational composite preparation.

The second obstacle involves the composite interface, specifically the interface connecting the matrix and the reinforcing phase, which is essential for achieving enhanced strength and toughness. The regions affected by the composite interface, such as the interfacial reaction-affected zone (IAZ) and the grain boundary-affected zone (GBAZ), demonstrate higher dislocation densities, thereby serving as significant contributors to energy dissipation [144]. Apart from controlling the structure and bonding state of the composite interface, an effective approach involves activating dynamic energy dissipation mechanisms, including interface migration and interface reconstruction. It is desirable to have an interface phase with a high energy consumption mechanism, which can undergo phase transformation [145] or special reactions [146]. This introduces energy dissipation mechanisms like deformation-induced phase transformation and reaction self-healing.

The fundamental concept for preparing multiphase and multi-scale composite configurations should adhere to the principle of "primitive assembly - limited composition - hierarchical construction." [95]. This entails assembling composite structural units with different characteristics, scaling up smaller units, and hierarchically constructing configurational metal matrix composites with diverse structural units. By integrating high-throughput characterization technology with multi-scale simulation [147,148], it is expected that precise and localized control of composite configurations can be achieved. This advancement will enable the design and preparation of new structured metal matrix composites with exceptional performance based on the theory of energy dissipation.

6. Summary and Outlook

6.1. Summary

This paper provides an overview of the configuration design concept for MMCs and highlights the advantages of heterogeneous nanostructured metals in terms of strength and toughness. It discusses the development history of configurational MMCs and emphasizes the need for quantitative analysis techniques to understand the strength and toughness mechanisms in composite materials. The demand for high strength and high toughness materials in aerospace and automobile industries is driving the development of MMCs that can achieve simultaneous strengthening and toughening. The potential of AMCs is highlighted, along with the challenges posed by the inverse relationship between strength and toughness in MMCs. The importance of design configuration in achieving simultaneous improvement in strength and toughness is emphasized, and inspiration from biological composites is discussed. Understanding fracture behavior and toughening mechanisms in heterogeneous nanostructures is crucial for advancing the field of MMCs, and composite architecture design offers immense potential for tailoring MMCs with exceptional strength and toughness.

6.2. Outlook

Moving forward, future research should focus on developing quantitative analysis techniques for energy dissipation and deformation nonlocalization, providing a comprehensive understanding of the strength and toughness mechanisms in composite materials. The use of energetic criteria for mechanical properties and service behavior can guide the reverse design of composite configuration/interfaces, enabling the realization of multi-scale configurational composite technology and overcoming the strength-toughness inversion bottleneck in MMCs. Researchers should also continue to explore strength-toughness matching strategies to address the inverse relationship between these properties in MMCs. Additionally, gaining insights from the architecture of biological composites, such as bone, can provide valuable inspiration for achieving exceptional strength and toughness in synthetic composites through hierarchical organization and the combination of different building blocks. Understanding fracture behavior and toughening mechanisms in heterogeneous nanostructures will be instrumental in advancing the field of MMCs. Overall, composite architecture design holds immense potential for tailoring MMCs with exceptional strength and toughness, meeting the demands of lightweight engineering structures across various industries.

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