Review Article

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Mechanical properties of nanomaterials: A review

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Abstract: As an emerging material, nanomaterials have attracted extensive attention due to their small size, surface effect and quantum tunneling effect, as well as potential applications in traditional materials, medical devices, electronic devices, coatings and other industries. Herein, the influence of nanoparticle selection, production process, grain size, and grain boundary structures on the mechanical properties of nanomaterials is introduced. The current research progress and application range of nanomaterials are presented. The unique properties of nanomaterials make them superior over traditional materials. Therefore, nanomaterials will have a broader application prospect in the future. Research on nanomaterials is significant for the development and application of materials science.

Keywords: nanomaterials, mechanical properties, materials science

1 Introduction

A nanomaterial refers to a material that has at least one dimension in a three-dimensional space or is reduced in composition to a nanoscale (1–100 nm) [1]. Nanomaterials can generally be classified into two types: nanostructured materials and nanostructured elements. In nanostructured materials, its structural dimensions are nanoscale. In nanostructured elements, at least one of the structural elements has an outer dimension within the nanometer range [2, 3]. Nanomaterials have unique properties compared with general materials. For example, the compressive and flexural strength of cement mortar with nano-SiO_2 or nano-Fe_2O_3 measured at the 28th day are both higher than those of the blank group [4]. Compared with microscale monolithic alumina ceramics, nano-Al_2O_3 ceramics have higher flexural strength [5].

Mechanical properties refer to the mechanical characteristics of materials under different environments and various external loads. Different materials exhibit different mechanical properties. As for the traditional materials, the mechanical properties of metals generally consist of ten parts, which are brittleness, strength, plasticity, hardness, toughness, fatigue strength, elasticity, ductility, rigidity and yield stress. Most inorganic non-metallic materials are brittle materials, which do not have properties such as plasticity, toughness, elasticity, ductility and so on. Besides, some organic materials are flexible materials, which do not have properties such as brittleness and rigidity.

Nanomaterials have excellent mechanical properties due to the volume, surface and quantum effects of nanoparticles. As nanoparticles are added to a common material, these particles will refine the grain to a certain extent, forming an intragranular structure or an intergranular structure, thereby improving the grain boundary and promoting the mechanical properties of materials [6–8]. For example, adding 3 wt/% nano-SiO_2 to concrete can improve its compressive strength, bending strength, and splitting tensile strength [9]. Adding 3% nano oil palm empty fruit string filler into kenaf epoxy composites can considerably improve their tensile strength, elongation at break, and impact strength [10].

Given that nanomaterials have excellent mechanical properties and unique properties that are not found in macroscopic materials, they have broad application prospects in the future. However, further research on nanomaterials must be conducted. We need to determine the mechanical properties of various nanomaterials to identify their possible engineering applications and industrial productions.

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2 Factors affecting mechanical performance of nanomaterials

2.1 Nanoparticle selection

Since Uyeda fabricated metal nanoparticles by gas evaporation condensation in the 1960s, research on nanomaterials has expanded. Thus far, scientists have made progress in nanotechnology research, discovering and developing many kinds of nanomaterials. Different nanomaterials have different mechanical properties. Hence, comparing the toughness of nanoceramic materials and natural nanomaterials is unreasonable. Thus, the selection of nanomaterials herein primarily refers to the nano-enhancement phase in the nanocomposites. We take nanoceramic composites as an example to introduce the influence of nanoparticle selection.

Figure 1 shows the variation law of fracture toughness and hardness with the increase of nano-Al_2O_3 content [11]. The fracture toughness and hardness obviously decrease after initially increasing with the increase in nano-Al_2O_3 content. When the nano-Al_2O_3 content reaches 4 vol.%, its fracture toughness and hardness reach the maximum. Therefore, adding a lot of nanoparticles to the matrix may reduce the mechanical properties of a nanocomposite [12].

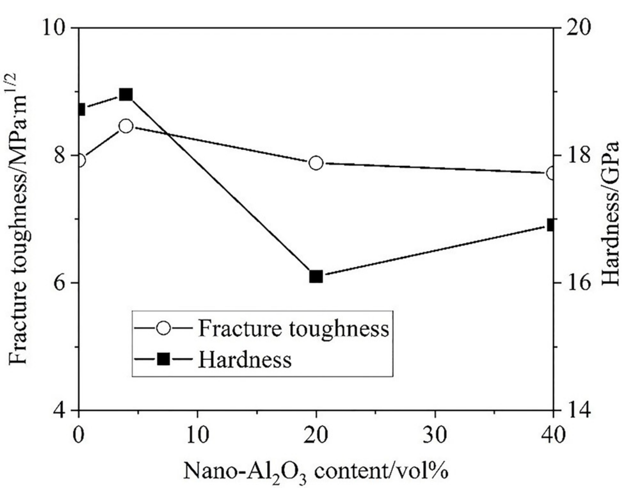

Figure 1: The effects of the content of nano-Al_2O_3 on the fracture toughness and hardness of a ceramic tool material [11]

Figure 2 shows the scanning electron micrographs of fracture surface with different nano-Al_2O_3 content. The grains become smaller with the decrease in nano-Al_2O_3, because SiC suppresses the grain growth process. According to the Hall–Petch relationship, flexural strength increases as the grain size decrease. Therefore, adding a lot of nanoparticles does not improve the mechanical properties of nanomaterials.

The addition of nano-TiN to cermet can also improve its mechanical properties. Table 1 shows the partial mechanical properties of general cermet and nano-TiN-modified cermet. Compared with general cermet, the nano-TiN-modified cermet has approximately 7%, 25% and 4% higher fracture toughness, bending strength, and hardness, respectively [13].

Table 1: Mechanical properties of nano-modified cermet and ordinary cermet [13]

Mechanical properties	Fracture toughness (MPa/m^2)	Bending strength (MPa)	Hardness (HRA)
Nano-modified cermet	12.7	1310	92.9
Ordinary cermet	11.9	1050	89.3

The addition of nano-ZrO_2 and micro-WC to cermet reduces its wear rate and surface friction coefficient [14]. Under the same conditions, the mechanical properties of nanocomposites with micro-TiB_2 and Al_2O_3 as the main body and nano-ZrO_2 as the second phase are higher than those of pure ZrO_2 nanomaterials [15].

A number of nano-reinforcing phases are added to the matrix to obtain nanocomposites with excel lent mechanical properties. Yi *et al.* [16] found that the mechanical properties of nanocomposites increase first and then decrease with the increase in TiB_2 content in the material; afterwards, these properties gradually increase with the increase in Al_2O_3 content. Liu *et al.* [17] added nanographene oxide and nano-SiO_2 in cement to enhance its mechanical properties. The flexural strength of the mixed cement increases by 42%, whereas the flexural strength of the nano-graphene oxide cement and nano-silica cement increases by 35.5% and 27.5%, respectively.

In general, the addition of nanoparticles can usually promote mechanical properties of matrix [18]. However, adding nanoparticles can reduce its mechanical properties in some cases [19, 20]. The fracture toughness, flexural strength, and hardness of a cermet composite can be better promoted by adding nano-TiN than by adding nano-Al_2O_3 to the matrix. In addition, the amount, ratio, and nanoparticle size have a certain impact on the mechanical properties of nanocomposites [21].

Therefore, when modifying materials to obtain better mechanical properties, we should consider not only the

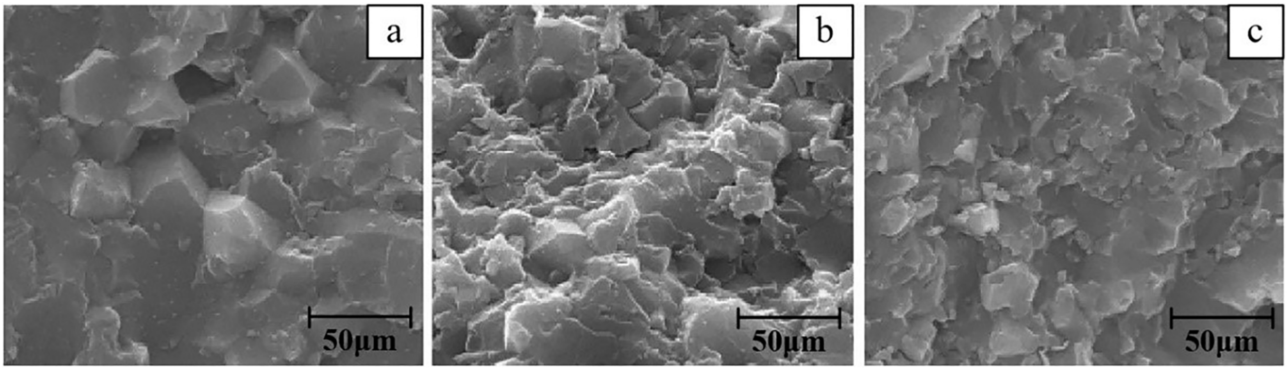

Figure 2: Scanning electron micrographs of fracture surface with different content of nano-Al_2O_3 [12]. (a) 80 wt% nano-Al_2O_3, (b) 70 wt% nano-Al_2O_3, (c) 60 wt% nano-Al_2O_3

types of nanoparticles but also factors such as the number or ratio of nanoparticles [22].

2.2 Production process

The effect of the production process on the mechanical properties of nanomaterials is mainly reflected in the processing parameters. The temperature, method, treatment time, nanoparticle dosage, and ratio will influence the mechanical properties of nanomaterials to some extent.

Different sintering temperatures have different influences on the mechanical properties of materials. Karimzadeh *et al.* [23] found that increasing the sintering temperature from 1000°C to 1300°C can improve the hardness of nano-hydroxyapatite (nano-HA), but further increase will reduce its hardness (Figure 3).

As the sintering temperature increases, the relative density, bending strength, and fracture toughness of Al_2O_3–TiC composite will gradually increase due to the decreasing number of pores and material densification (Figure 4) [24]. Compared with unsintered nano-HA, the powdered crystallinity of nano-HA after sintering is substantially increased, and its elastic modulus and hardness are correspondingly increased [25].

The effects of different nanoparticle contents on the mechanical properties of the matrix are also different. Thind *et al.* [26] reported that nanocomposites with improved tensile strength, flexural strength, hardness, and specific wear rate can be obtained by adding 2 wt/% nano-clay to the epoxy resin matrix. However, as the content of nano-clay continues to increase, their mechanical properties decrease to varying degrees. The addition of graphene oxide can accelerate cement hydration, improve the microstructure of hydrated crystals, and considerably reduce the pore size of graphene oxide-modified cement slurry,

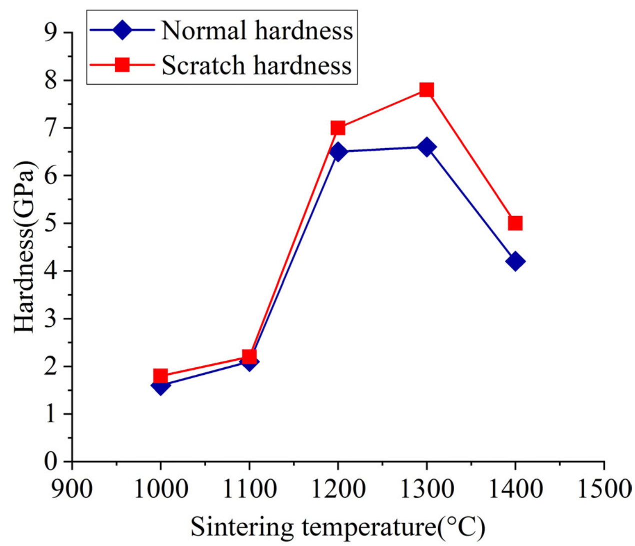

Figure 3: Variation law of normal hardness and scratch hardness with increasing sintering temperature [23]

thereby improving the mechanical properties of composites [27]. When the amount of graphene oxide is 0.03 wt/%, the tensile strength, flexural strength, and compressive strength of the cement are remarkably improved [28]. As the content of graphene oxide reaches 0.05%, its compressive strength and flexural strength increase by 33% and 41%, respectively [29]. As shown in Figure 5A, the distribution of hydrated phases is non-uniform. Many macropores and microcracks exist. However, the addition of graphene oxide nanoplatelets (GONPs) modifies the microstructure and results in more uniform and compact structure as they cause bridging between cement hydrates (Figures 5a-5f).

Different wet states can also have different effects on the mechanical properties of nanomaterials. Khorasani *et al.* [30] found that the tensile strength and maximum load capacity of polyvinyl alcohol/chitosan/nano-ZnO hy-

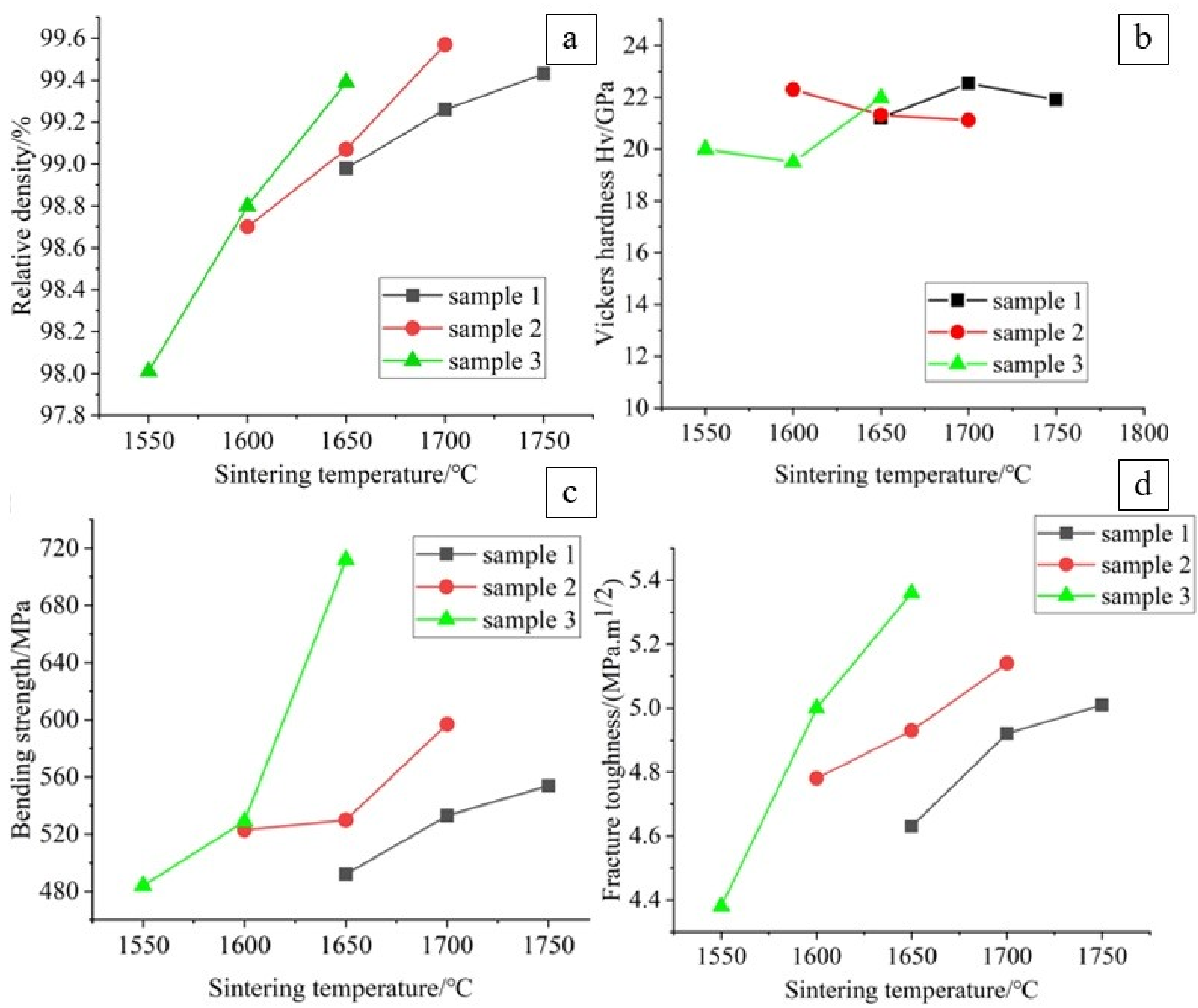

Figure 4: Variation law in the properties of Al_2O_3–TiC composites with sintering temperature [24] (a) Variation law of relative density with sintering temperature, (b) Variation law of Vickers hardness with sintering temperature, (c) Variation law of bending strength with sintering temperature, (d) Variation law of fracture toughness with sintering temperature

drogel increase with the increase in nano-ZnO content in the dry state, whereas the elongation at break increases first and then decreases. In the wet state, the tensile strength and maximum load capacity remarkably decrease, whereas the elongation at break obviously increases.

The processing time of ultrasonic wave also has a certain effect on the mechanical properties of nanomaterials [31]. As the ultrasonic treatment time increases, the density of nanocomposites decreases after it initially increases. The maximum density is obtained when the treatment time is 30 min [32], which may be caused by the cavitation effect of ultrasonic processing [33]. At the initial stage, the ultrasonic vibration promotes the movement of nanoparticles within the material. The pores inside the material are gradually filled by nanoparticles, and the material becomes dense, resulting in excellent mechanical properties [34]. With the increase of vibration time, the nanoparticles that have been in the pores of the matrix material continue to move, forcing their way out of the pores and into the positions between the crystals of the matrix material, which weakens the grain boundary strength of the matrix material. Thus, the mechanical properties of the material are reduced. When the sonication time exceeds 30 min, the elongation at break of the nanomaterial remarkably increases, but the tensile strength decreases. When the treatment time is 1 h, additional pores are formed on the surface of the material, leading to a decrease in the mechanical properties of the material [35].

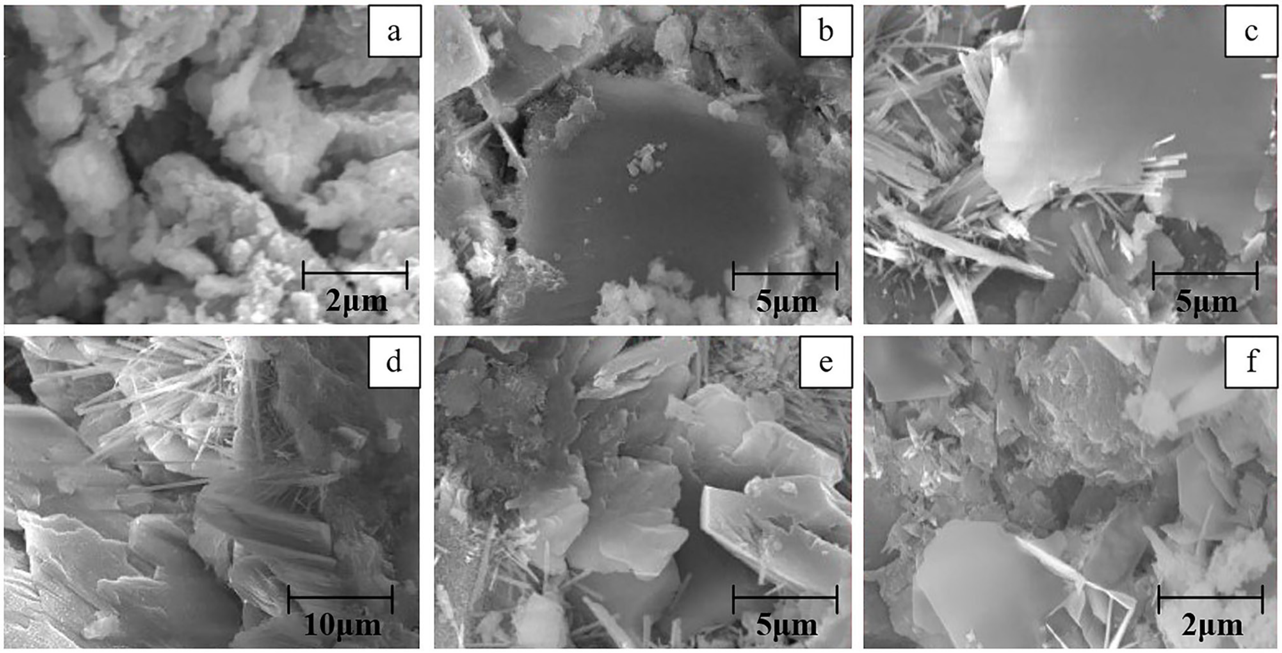

Figure 5: Scanning electron micrographs of cement composites obtained at the 28th day after curing for ordinary Portland cement–GONPs composites modified by different contents of GONPs [27] (a) no GONPs, (b) 0.01% GONPs, (c) 0.02% GONPs, (d) 0.03% GONPs, (e) 0.04% GONPs, (f) 0.05% GONPs

2.3 Grain size

Nanomaterials are mainly composed of nanograins and grain boundaries. Therefore, grain size is one of the main factors affecting the mechanical properties of nanomaterials [36]. In recent years, the relationship between grain size and mechanical properties has been widely investigated [37, 38]. Wang *et al.* [39] used X-FEM and Voronoi models to simulate the crack propagation of ceramic materials and studied the effect of grain size on the process. Zhou *et al.* [40] used the Voronoi mosaic method to characterize the microstructure of unidirectional ceramic tool and studied the effect of grain size on the fracture form and fracture resistance of the material. Acchar *et al.* [41] found that the addition of nano-NbC particles to nano-alumina increases its porosity, resulting in a slight decrease in flexural strength. Trombini *et al.* [42] found that the addition of nano-NbC in Al_2O_3 matrix was efficient in inhibition grain growth which will result in an increase in mechanical strength. However, larger NbC particles may act as a defect in the structure, causing a small reduction in strength. Figure 6 shows that the addition of NbC does not effectively inhibit grain growth as compared with earlier studies that used micro-alumina [43–45].

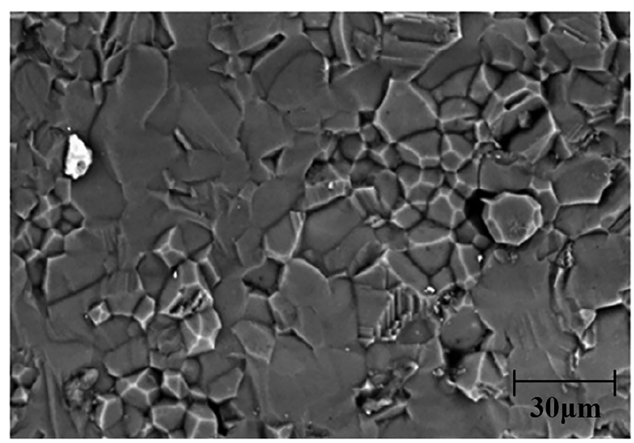

Figure 6: Surface fracture of alumina-NbC [41]

The effect of grain size on the mechanical properties of nanomaterials is mainly reflected in the microstructure. Nanoparticles have a considerable size effect and high surface activity. Given that nanoparticles are small, their addition can fill the matrix's pores, reduce its porosity, increase its relative density, and improve its mechanical properties. Liu *et al.* [17] found that adding nanomaterials to cement slurry can improve the pore structure of hardened cement paste and make it denser (Table 2). The average pore size and total porosity of nano-cement has obviously decreased by 16.9% and 25.5%, respectively, compared with that of the blank cement.

Moreover, the addition of nanoparticles can reduce the size of crystal grains, promote the densification of ma-

Table 2: Pore structure parameters of different samples [17]

Sample	Mercury intrusion volume (mL/g)	Average pore diameter (nm)	Total porosity (%)	Total surface to volume ratio (mL/g)
Blank cement	0.220	19.5	32.38	46.374
GO cement	0.207	18.	32.04	44.475
Nano-silica cement	0.196	17.1	30.01	44.233
Hybrid cement	0.171	16.2	24.12	42.880

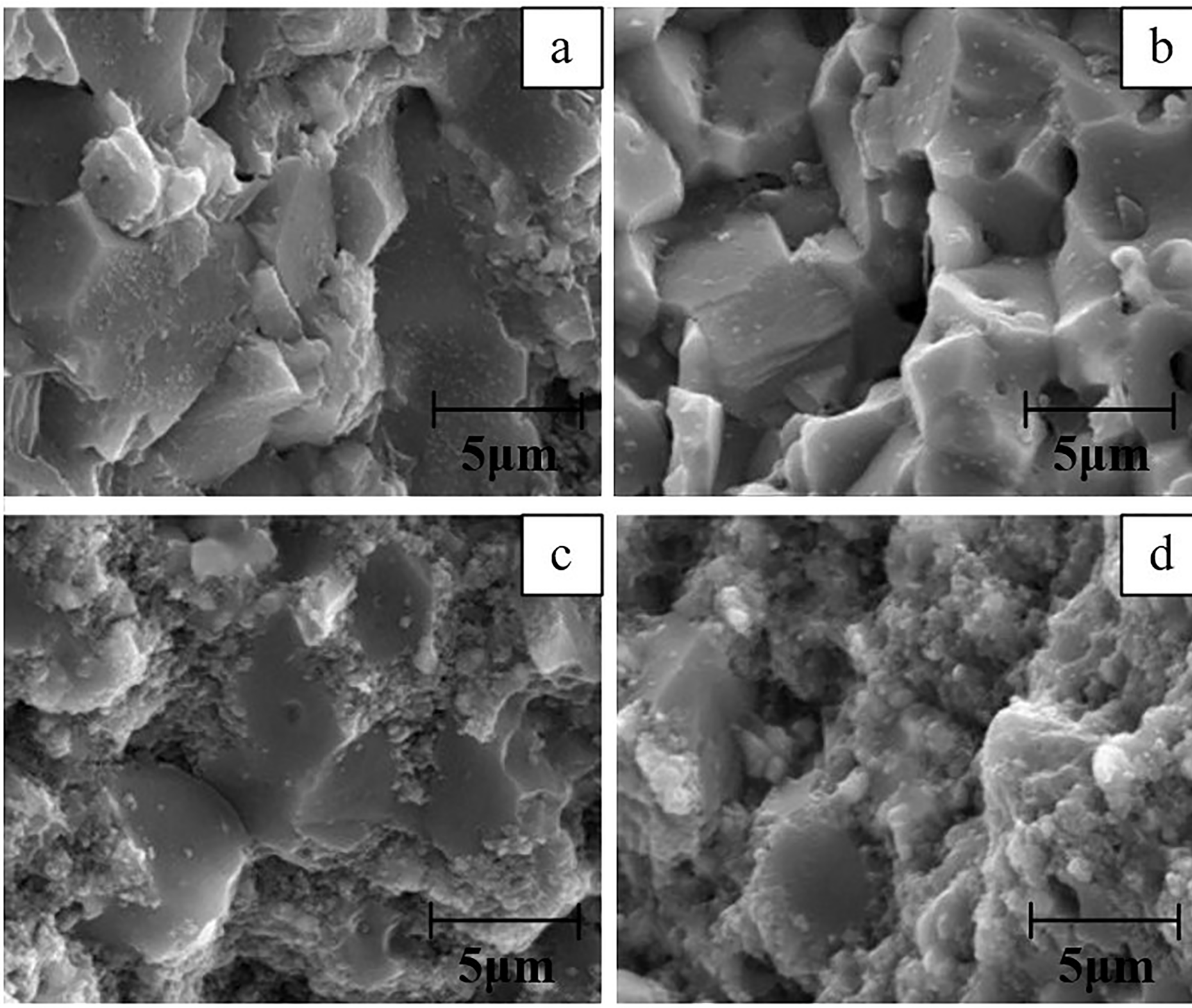

Figure 7: Scanning electron micrographs of the fractured surface of nano-micro composite self-lubricating ceramic tool material with different content of Al_2O_3 [11] (a) 0 vol.% nano-Al_2O_3, (b) 4 vol.% nano-Al_2O_3, (c) 20 vol.% nano-Al_2O_3, (d) 40 vol.% nano-Al_2O_3

terials, and reduce defects such as pores. The pinning effect of nanoparticles can improve the growth of twins during sintering, inhibit the abnormal growth of crystal grains, and limit the shape so that the grains inside the material exhibit reasonable shape and size. Fine grains can inhibit the cleavage fracture of the material. Therefore, the mechanical properties of the material can be improved. Yi *et al.* [11] found that the addition of a proper amount of nano-Al_2O_3 can reduce the grain size of ceramic tool materials and inhibit the abnormal growth of grains. However, excessive nano-Al_2O_3 results in the appearance of agglomerates that increase the porosity of the materials and eventually lead to the decline in their mechanical properties. The variation in the microstructure with the amount of nano-alumina is shown in Figure 7.

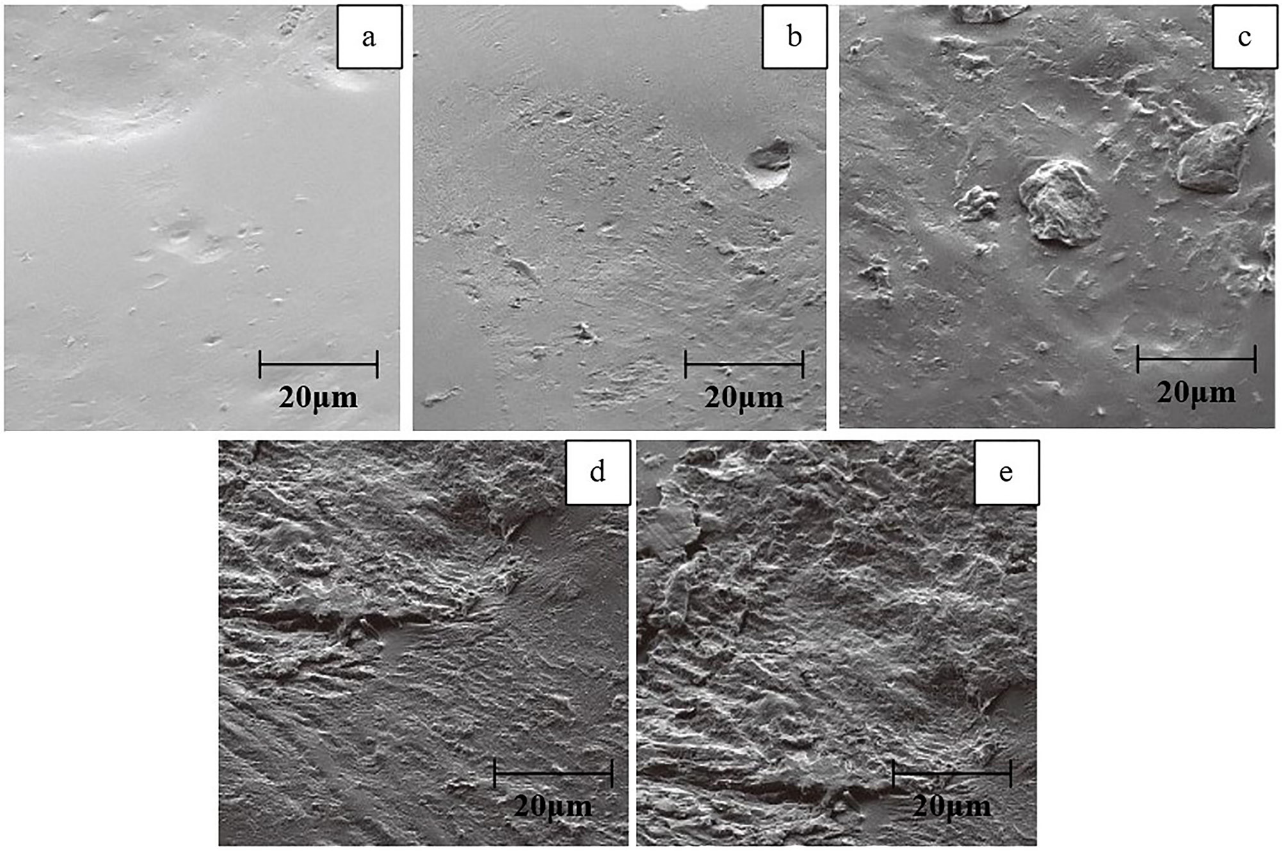

Figure 8: Scanning electron micrographs of fracture surfaces with different nano-HA contents [51] (a) PLLA; (b) 10% nano-HA; (c) 20% nano-HA; (d) 30% nano-HA; (e) 40% nano-HA

2.4 Grain boundary structure

Owing to the size effect of nanomaterials, the grain boundaries of nanomaterials have a higher volume fraction than microscale and traditional materials [46]. In composites, good bonding between the filler and the matrix is critical to improving their mechanical properties [47–49]. Therefore, grain boundaries are one of the important factors affecting the mechanical properties of nanomaterials, especially nanocomposites. In general, the denseness, chemical bonding properties, and structural properties of the grain boundaries affect the mechanical properties of nanomaterials. Accordingly, the factors that can affect grain boundary structure also indirectly affect the mechanical properties of nanomaterials.

Researchers can modify the matrixes by adding nanoparticles to improve their mechanical properties [50]. Thind *et al.* [26] increased the flexural strength of epoxy resin matrix by adding nano-clay. When the mass fraction of nano-clay in the composite was 2%, its flexural strength was increased by 77%. The principle of this method is to improve the interfacial structure of the matrix by adding nanoparticles and to use the size effect of the nanoparticles to fill the pores in the interface of the matrix to make it denser, thereby indirectly improving its stress transmission and elasticity. The interface performance caused by deformation improves the mechanical properties. Zhu *et al.* [51] found that adding 20 wt% nano-HA to poly-L-lactic acid (PLLA) can improve its toughness because of the formation of a coating of polymer matrix-coated nano-HA at the interface. The coating facilitates stress transfer and prevents crack propagation, thereby increasing the toughness of the composite. Figure 8 shows the scanning electron micrographs of the fracture surfaces of nano-HA/PLLA composites with different nano-HA contents.

Many other methods, such as high-temperature sintering and thermal cycle loading, are used to improve the mechanical properties of nanomaterials. Zucchelli *et al.* [52] found that high-temperature sintering of enamel–steel systems can increase its complex diffusion process and the diffusion of iron in steel (Figure 9). Fe^{3+} is the best network modifier [53]. The diffusion of Fe^{3+} improves the structure of the enamel–steel interface. The combination of the two phases promotes the mechanical properties and improves

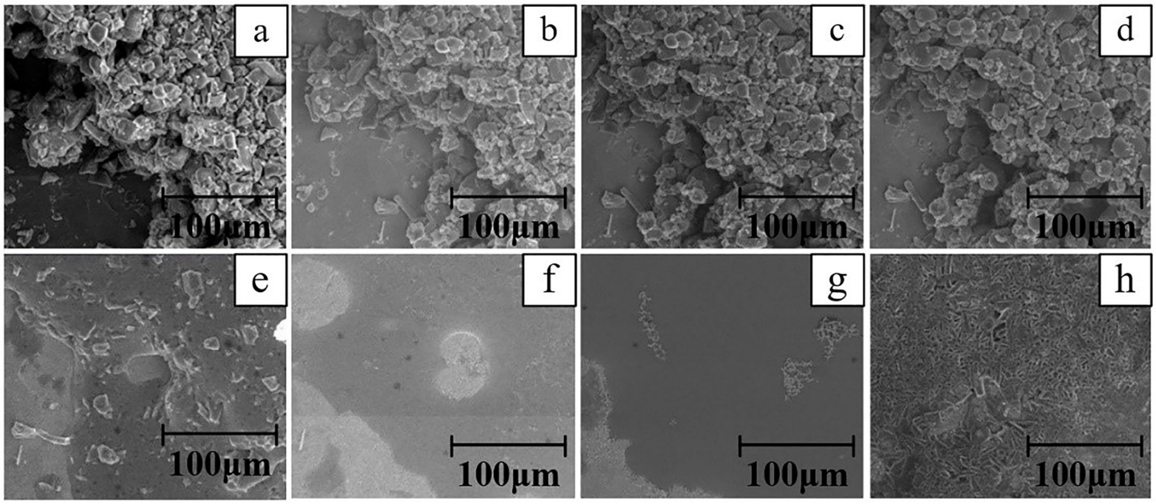

Figure 9: *In situ* micrographs of studied enamel during heating at different temperatures [52]

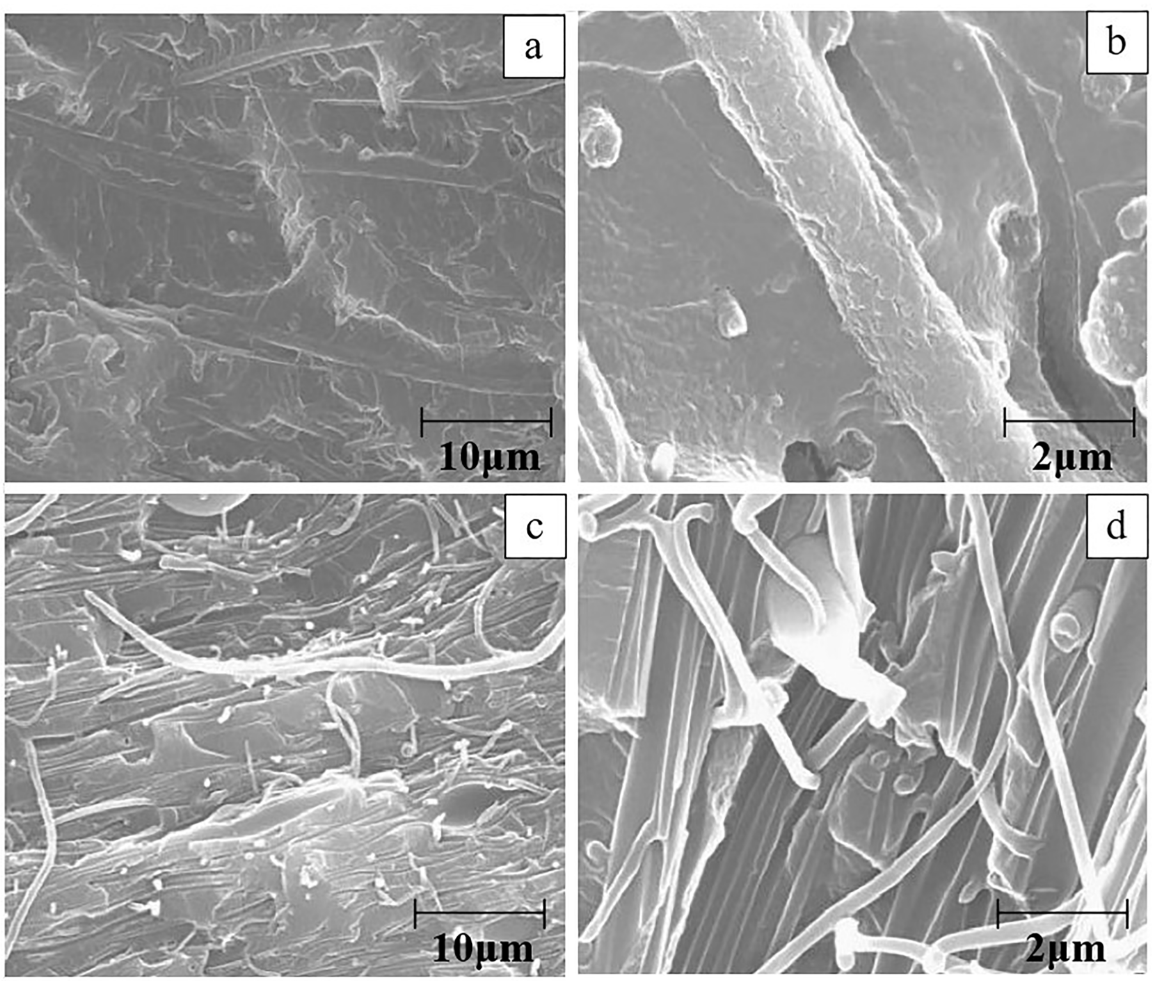

Figure 10: Scanning electron micrographs of fracture surfaces of three-point flexural testing specimens [55] (a) Low magnification of PAN–PMMA nanofibers, (b) high magnification of PAN–PMMA nanofibers, (c) low magnification of PAN nanofiber, (d) high magnification of PAN nanofiber

Table 3: Mechanical properties of metal nanomaterials [56, 57]

Sample	Vickers hardness (GPa)	Fracture toughness (MPa$\sqrt{m}$)	Fracture strength (MPa)	Ultimate Tensile Strength (MPa)	Impact Strength (J/cm^2)
Monolithic Al_2O_3	17.8	3.6±0.3	536±35	——	——
Al_2O_3/Cu(oxide)	17.0	4.9±0.7	819±53	——	——
Al_2O_3/Cu(nitrate)	17.2	4.8±0.2	953±59	——	——
Al_2O_3/Ni-Co	19.0	4.3±0.5	1070±72	——	——
AA6061/nano SiC	96.38	——	——	190.21	15.5
AA6061/nano B_4C	69.39	——	——	201.54	12.36
AA6061/1.5SiC+1.5B_4C	173.97	——	——	280.18	19.75

the interface hardness and elastic modulus of the enamel–steel interface. Zhang *et al.* [54] improved the elastic modulus and hardness of Cu/Cr nano-interface by thermal cycling. By controlling the parameters such as loading speed and cooling rate, grain growth, nucleation, and other processes can be controlled, and defects such as pores in the Cu/Cr nano-interface can be reduced. Lin *et al.* [55] made nanofibers and matrix interpenetrate and entangle each other through photopolymerization technology, forming an in situ nano-interface that has a strong interface bond between nanofibers and matrix (Figure 10).

In addition to the aforementioned methods for modifying the interfacial properties of nanomaterials, many other modification methods can achieve the same purpose. Their principles are undeniably similar and can be roughly divided into two types. The first type is to improve the interfacial properties and increase the interfacial bonding of nanomaterials by adding nanoparticles to the matrix to fill the pores of the interface structure of the matrix. The second type is to improve the interface of nanomaterials by processing nanomaterials, enhancing the component diffusion process between two-phase or multi-phase materials, or controlling the growth process of crystal grains.

3 Mechanical properties of nanomaterials

Mechanical properties of nanomaterials refer to the mechanical characteristics of nanomaterials under different environments and various external loads. A large amount of literature has studied the mechanical properties of nanomaterials. However, these studies mainly focus on improving the mechanical properties of nanomaterials by adding nanoparticles to the matrix which is generally not a nanomaterial. Few researches on the mechanical properties of pure nanomaterials are studied. More details of mechanical properties of metal nanomaterials obtained including Vickers hardness, fracture toughness, fracture strength, ultimate tensile strength, as well as impact strength are provided in Table 3.

It can be seen that nanomaterials with metal nanoparticles have higher fracture toughness and fracture strength than monolithic Al_2O_3. This phenomenon should be attributed to the addition of nanoparticles. The pinning effect of metal particles inhibits the grain growth of Al_2O_3 matrix, making the grain size of the nanocomposite smaller than that of monolithic Al_2O_3, resulting in grain refinement, and leading to the improvement of mechanical properties of the nanocomposite [56]. Interestingly, the hardness of nanocomposites with nano-Cu is lower than that of monolithic Al_2O_3, while the hardness of nanocomposites with nano-Ni-Co is higher than that of monolithic Al_2O_3, which is probably due to the reason that the hardness of Cu is lower than that of Al_2O_3, and the addition of nano-Cu weakens the hardness of nanocomposites to some extent. Similarly, the hardness of nano-Ni-Co is higher than that of Al_2O_3. The addition of nano-Ni-Co increases the hardness of nanocomposites to a certain extent. In addition, the last three sets of data in Table 3 show that the hybrid composites have higher Vickers hardness, impact strength and ultimate tensile strength compared to the single reinforced composites due to the combined effect of SiC and B_4C.

Table 4 shows the mechanical properties of non-metallic nanomaterials. It is obviously that the addition of multi-walled carbon nanotubes to skutterudites will lead to a decrease in the mechanical properties of the nanocomposite. This is due to the formation of carbon nanotubes agglomerates inside the skutterudites. The plane like agglomerates act as slip planes and planes in which cracks can easily propagate, thereby leading to sample fracture already at low mechanical loads [58]. It is undeniable that

Table 4: Mechanical properties of non-metallic nanomaterials [51, 58, 59]

Sample	Vickers hardness (GPa)	Compressive strength (MPa)	Flexural strength (MPa)	Tensile strength (MPa)	Elongation at break (%)	Young's/ Bending modulus (GPa)
p-type skutterudites	576±52	630±20	105±10	——	——	44±8
p-type skutterudites+ 0.5 wt% multi-walled carbon nano tubes	513±52	355±15	65±7	——	——	40±6
p-type skutterudites+ 1.0 wt% multi-walled carbon nano tubes	563±85	320±15	54±7	——	——	39±8
p-type skutterudites+ 1.5 wt% multi-walled carbon nano tubes	569±70	255±10	45±5	——	——	33±10
oil palm empty fruit bunch fiber	——	——	——	50-400	8-18	1-9
Kenaf fiber	——	——	——	500-600	1.5-3.5	40-53
100% nano-PLLA	——	——	135.6	55.6	——	3.3
90% nano- PLLA+ 10% nano-HA	——	——	142.5	53.2	——	3.5
80% nano- PLLA+ 20% nano-HA	——	——	156.8	48.6	——	3.8
70% nano- PLLA+ 30% nano-HA	——	——	130.3	42.3	——	3.9
60% nano- PLLA+ 40% nano-HA	——	——	125.9	38.6	——	4.1

most organic nanomaterials do not have mechanical properties like hardness and compressive strength, because most nanomaterials are flexible materials.

The last five groups of data in Table 4 show that the tensile strength gradually decreases with the increase of nano-HA which may be related to the fragile interface between nano-HA and nano-PLLA. The flexural strength of the nanocomposites first increased and then decreased with the increase of nano-HA. When the nano-HA content reaches 20%, the bending strength reaches a maximum of 156.8 MPa.

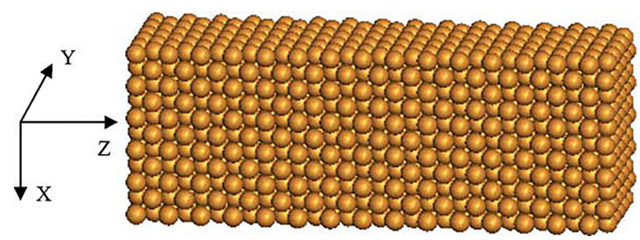

Figure 11: Simulation model of Cu nanowire [63]

4 Research progress

In recent years, nanomaterials have received widespread attention due to their unique properties and their importance in technical applications. Many researchers have begun research work on nanomaterials [60]. These researches mainly focus on three aspects: theoretical research, simulation analysis and experimental study.

In theoretical research, Tseng *et al.* [61] proposed a constitutive model framework to predict the mechanical properties of nanoparticle-reinforced composites and compared the predicted results of the model with the experimental results. Zahedmanesh *et al.* [62] proposed a method for fast derivation of the effective orthotropic elastic moduli of complex multilayer nano-interconnects and corroborated it with the finite element modelling.

As for simulation analysis, Wu [63] studied the mechanical behavior of Cu nanowires by molecular dynamics method, and obtained the stress-strain relationship of nanowires through numerical simulation (Figure 11). Wang *et al.* [64] simulated the uni-axial tension process of nano-twinned Cu with silver inclusions by molecular dynamics method, and found that decreasing the volume fraction of Ag or increasing the size of Ag will lead to the increase of the ultimate strength of nano-twinned materials (Figure 12).

In terms of experimental study, researchers are focusing on modifying nanomaterials, that is, improving the mechanical properties of nanomaterials [65]. At present, a common method is to add nanoparticles to the matrix to improve the mechanical properties of the nanomaterials. For example, the strength of functionally graded materials can be enhanced by adding carbon nanotubes [66]. The

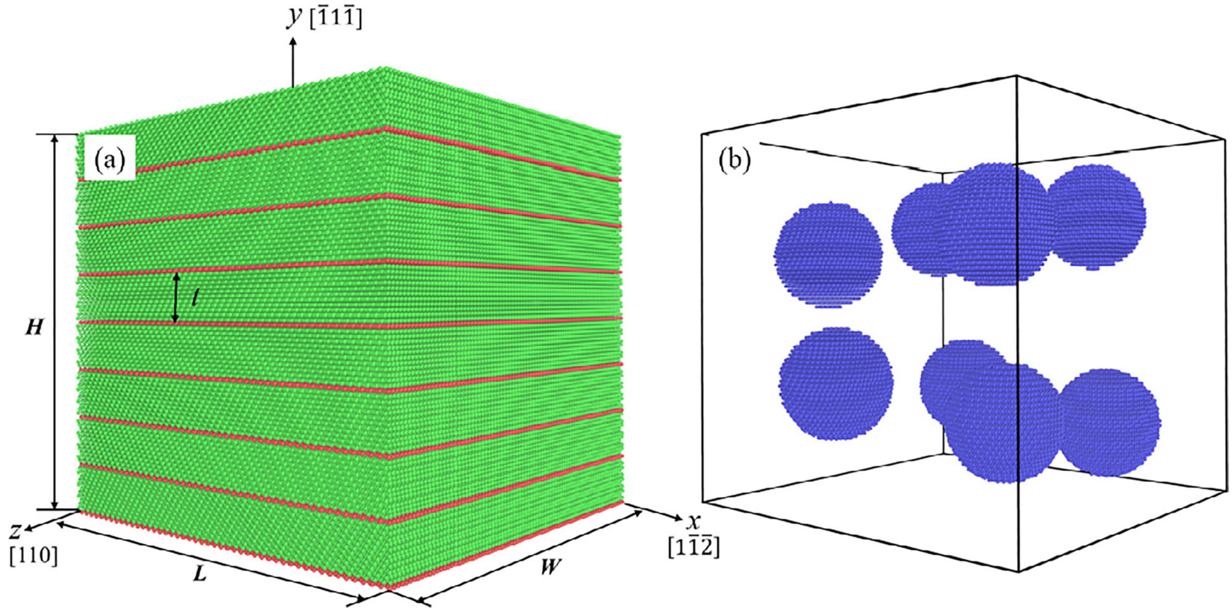

Figure 12: The three-dimensional schematic diagram of the simulated nano-twinned Cu with spherical Ag inclusions [64] (a) Simulation model (b) The same structure without Cu atoms. In addition, the green and red atoms are respectively the atoms which are in local fcc and hcp lattices. The blue atoms represent the silver atoms

mechanical and tribological properties of bone cement can be improved by adding nano-HA [67]. The mechanical properties of the matrix can be improved by adding electrospun polymer nanofibers to the matrix [68, 69]. Lin *et al.* [70] found that strong interfacial interactions between graphene oxide fillers and polyvinyl alcohol matrices can be achieved by metal ion coordination, providing a new way to prepare polymer-based nanocomposites with considerably improved mechanical properties. In addition, some researchers are also investigating the process parameters to promote nanomaterial performance or microstructure. They are attempting to identify the mechanisms that improve the performance of nanomaterials by determining the optimal process parameters or methods to construct nanomaterials [71, 72]. Daudin *et al.* [73] found that the modification of the casting conditions can obtain different microstructures, thereby improving the high temperature mechanical response of the Elektron21+AlN materials.

5 Application

Metal nanoparticles are the first artificially prepared nanoparticles. Compared with other nanomaterials, nanometal materials have the longest development time, and thus, they have been extensively researched. Nanometals, such as gold, silver, and zinc, have been widely used to improve the physical, chemical, and mechanical properties of various materials, including paper, archaeological stone, paint, wood, and medical equipment. A functionalized polymer containing nano-Ag can be used not only as an effective fungicide but also as a reinforcement of historical and cultural relics [74]. The addition of nano-Zn can improve the leaching and corrosion resistance of Nanhuang pine [75]. Nano-Ag and nano-Cu can improve the antibacterial properties of commercial particleboard and increase its lifespan [76]. In addition, some nano metal compounds have also been used in catalysts, antibacterial and antiseptic research [77–79].

With regard to inorganic non-metallic nanomaterials, researchers are focusing on nano-cement and nano-concrete. Their mechanical properties are improved by adding nanoparticles to cement-based materials or concrete and promoting the dispersion of nanoparticles in the matrix [80, 81]. Nano-Si has excellent properties, such as high melting point, high hardness, and high chemical stability. It is a promising candidate for improving the performance of cement-based materials [82–84]. The addition of the nano-Si could produce an increase in the compressive and flexural strengths of the cement mortar [85].

Aside from nanometal materials and inorganic non-metal nanomaterials, scientists have made progress in organic nanomaterial research [86–88]. They have attempted to incorporate graphene oxide into polyvinyl alcohol nanofibers to obtain nanocomposites with better mechanical properties [89, 90]. Wang *et al.* [91] used graphene oxide (GO) in the improvement of polyvinyl alcohol (PVA) nanofibers to increase the degree of crystallinity and tensile strength. Kashyap *et al.* [92] observed ~150% increment both in elastic modulus and tensile strength while adding 0.3 wt% GO to PVA. Graphene oxide-doped polyvinyl alcohol nanofibers can be used as a hard template to assist the growth of TiO_2. Compared with nano-SiO_2 coated and uncoated samples, nanographene oxide/graphene oxide coating has more effective antibacterial activity and higher corrosion resistance in vitro; hence, these materials are expected to be applied to food packaging or protective coating of metal parts such as gears and rods [83].

6 Analysis and conclusion

This article mainly introduced the influence of four different factors on the mechanical properties of nanomaterials, namely, nanoparticle selection, production process, grain size, and grain boundary structure. These factors do not affect the mechanical properties of nanomaterials individually but interact and depend on each other. Using different materials and processing techniques will allow us to obtain nanomaterials with different microstructures and mechanical properties. The accumulation of various factors leads to the differences in mechanical properties between nanomaterials. In addition, on the basis of previous studies, we also introduced the current research progress of the mechanical properties and application prospects of nanomaterials.

Some studies on nanomaterials have achieved substantial results. Some nanomaterials have been applied to industrial production. However, related works on the molding mechanism and strengthening process of the microstructure of nanomaterials are still relatively few, and many areas still need to be explored. The unique properties of nanomaterials endow them with broad application prospects and huge potential value in the future. Therefore, we need to continue investigating nanomaterials and deepen our understanding of their molding mechanism, strengthening process, and modification methods to improve their properties.

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