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Endowing molecular motions in the solid materials Jiachen Guo, Jianbin Huang and Yun Yan



Building macro continuous materials that play an important role in our daily lives directly from powder is in line with the development needs of green chemistry. Powders or particles tend to spontaneously aggregate and fuse to reduce the interfacial energy of the system, but compared to solutions or melts, the molecular motion ability in the solid phase is significantly limited. Inspired by the agglomeration of powder and kneading dough, the introduction of a small amount of water and pressure has enabled the preparation of continuous self-supporting materials based on surfactants, and even the construction of ordered molecular membranes through solidphase molecular self-assembly. This article summarizes the recent work on the construction of macroscopic materials using molecular motion in solid phase, and mainly introduces its principles, self-healing properties, and application directions, including strain sensing, oil absorption, humidity response, circularly polarized luminescence, etc., and looks forward to the future development space.

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Introduction

Macroscopic continuous materials play an indispensable role in our society, including gels [1-3], films [4-7], etc. The mixing of several kinds of substances is the most commonly used method to improve material properties and endow materials with multiple functions [8-11]. While a substance is often processed into powder or particles after synthesis, in order to facilitate storage. Naturally, the simplest and most direct way to convert powder into macroscopic continuous materials is hoped to be achieved.

In fact, the phenomenon of micrometer sized particles agglomerating into blocks after moisture absorption is very common in daily life [12-15], such as milk powder, cocoa powder, fertilizers, etc. which can give us inspiration for obtaining macroscopic continuous materials through powder. And thousands of years ago, people had already mastered the technique of making flour into dough - with just a small amount of water and repeated kneading. During this process, protein components change their natural conformation, become stretched, and move to form a bridge between starch particles in the form of gluten [12,16-18]. Although molecules in the solid phase are traditionally considered to have weak mobility, similar processes have been found not only in soft matter, such as polymers, but also in hard inorganic particle systems, with the help of pressure and a small amount of solvent.

This article focuses on the material construction methods based on molecular motion in the solid phase, from powder to macroscopic continuum, and even to microscale ordered self-supporting materials based on surfactants, including principles and applications. In today's world that emphasizes effective resource utilization and environmental friendliness, this material construction method can not only maximize the utilization of raw materials, but also reduce the use of solvents, especially volatile organic solvents that are harmful to the environment, providing new ideas for the development of materials science.

Feasibility of molecular rearrangement in solid phase

Compared with macroscopic continuous materials, powders have more surface area and higher surface energy, which means that they tend to spontaneously fuse and reduce the total energy of the system thermodynamically [19]. But at the molecular scale, it is the movement and rearrangement of a large number of molecules that lead to the disappearance of boundaries between solid phases, which is often considered less likely to occur from a dynamic perspective.

Research has shown that a small amount of solvent is necessary, usually water [20,21]. Because it can disrupt the interaction between interfacial molecules and the

bulk phase, activate its migration, and give it a brief stabilizing effect through solvation interactions, which prevents the system energy from rising too high. Specifically, water molecules can temporarily stabilize the interaction sites of surfactants, hydrophilic polymers, and ions by utilizing their polarity and ability to form hydrogen bonds, reducing the energy barriers required for molecular diffusion, rearrangement, and reassembly. At the same time, solvent molecules also increase the molecular motion space because more non-covalent interactions are introduced, which are relatively weak and allow for relative movement between molecules [22].

In addition, pressure can also promote the rearrangement of molecules in the solid phase, as it can reduce the distance required for molecules to cross the interface and even promote the formation of material transport channels [21], such as water channels, thereby promoting the fusion of particles or powders.

Self-healing properties based on molecular rearrangement in solid phase

As the concept of a low-carbon society continues receiving global attention, the importance of materials with self-healing and recycling capabilities has become increasingly prominent [23-28]. Due to the use of molecular rearrangement in the solid phase during the initial construction of the material, even after being damaged, the molecules can still reduce the system interface energy in the same way, restoring it to its original state for reuse.

Many gels are self-healing, based on the concept of constitutional dynamic chemistry, especially when solvent molecules with high mobility can form "mobile phase" to fill cracks [29–31]. For example, the ionic hydrogel constructed by deep electrostatic solvents (DES) and flour (Figure 1a) [32], and the organic hydrogel PEI@HPs-PAM composed of polyethylene (PEI), polyacrylamine (PAM), and hydrophobic particles (HPs) (Figure 1b) [33].

If there are small molecules with strong migration ability in the building blocks of the system, such as surfactants, this repair process is more likely to occur, requiring only a small amount of solvent water at the interface, such as the film TPE-BPA/DEAB/Zn(NO₃)₂ constructed by dodecyl ammonium triethylammonium bromide (DEAB) and four-armed amphiphile TPE-BPA [34] (Figure 1c).

In addition, multiple studies have shown that supramolecular materials formed by surfactants and counter charged polyelectrolytes can achieve the re pressing of fragments into new films when immersed in water, and the mechanical properties and transparency of the films





(a) Optical microscopy images of the self-healing process of the ionic dough [32]. (b) Self-healing property of PEI@SiO₂/PAM hydrogel [33]. (c) The welding of two pieces TPE-BPA/DEAB/Zn(NO₃)₂ film under a load [34]. (d) Renewability of DTAB-PSS-CNT-urea films [37]. (e) Regeneration process of SA-DTAB films [35]. (f) Recycling process of the PDDA-AES films [36].

are similar to those of the initial films. For example, sodium alginate (SA) and DTAB (Figure 1d) [35], polydiallyl dimethylammonium chloride (PDDA) and fatty alcohol polyoxyethylene ether sulfate (AES) (Figure 1e) [36], dodecyltrimethylammonium bromide (DTAB) and sodium polyphenylene sulfonate (PSS) (Figure 1f) [37], etc.

Repair of the fracture is not directly related to the structure of the molecules used, indicating that selfhealing and cyclic regeneration are inherent properties of this type of material.

Materials inspired by kneading the dough Materials based on dough

Dough is a common ingredient in our cooking, obtained by mixing and kneading flour, with good flexibility, plasticity and adhesion, which are also the properties we hope to meet in the development of wearable flexible electronic devices today [38–42].

Han et al. mixed graphene oxide solution with wheat flour and kneaded it into a uniform dough [43]. Afterwards, wash the dough with water to remove starch particles and water-soluble components, and replace the solvent with a glycerol solution. Finally, the organic hydrogel (GGOH_x) was obtained by reducing graphene



Gluten-based organic hydrogels $GGOH_x$ [43]. (a) Schematic illustration of the fabrication of $GGOH_x$. (b) Proposed adhesiveness mechanism and photographs between GGOHx and various substrates. (c) Photographs of $GGOH_x$ under twisting and stretching after cooling at -20 °C for 7 days. And the conductivities of $GGOH_x$ at 25 °C and -20 °C. (d) Durability test of $GGOH_x$ sensors under a strain of 80% for 4000 cycles.

oxide with ascorbic acid (Figure 2a). The protein network and rich functional sites endow the material with excellent toughness (>1.83 MJ) and adhesion to various surfaces (Figure 2b). Due to the addition of glycerol, it has good water retention and low temperature resistance compared with ordinary hydrogels, and can even maintain mechanical properties and conductivity in the environment of -20 °C (Figure 2c). Meanwhile, the material can serve as a sensor to sensitively detect mechanical deformation and exhibit stable current changes ($\Delta I/I_0$) at a tensile strain of 80% in 4000 cyclic tensile tests (Figure 2d).

Chen et al. used glycerol and choline chloride (ChCl) to form deep electrostatic solvents (DES), which were mixed with flour and water to obtain ionic dough (Figure 3a) [32]. The introduction of DES not only broadens the stable temperature range of traditional dough, from -20 °C to 80 °C (Figure 3b), but also endows the material with good conductivity. Due to the fact that the material is based on dough, it can be molded into various shapes, similar to dough figurine in traditional Chinese folk art (Figure 3c), and can be degraded in moist soil (Figure 3d). As the strain increases, the resistance of the ionic dough increases, making it a wearable strain sensor (Figure 3e).

Materials based on hydrogels

In addition to the dough obtained from flour, viscoelastic hydrogels with similar mechanical properties can also be regarded as a good carrier platform. Wu et al. takes the hydrogel formed by polyacrylic acid (PAA) and amorphous calcium carbonate (ACC) as the model system [44], and adds the commonly used onedimensional (1D), two-dimensional (2D), threedimensional (3D) nano fillers to it, which can even allow the mixing of a variety of "condiments", so that the materials have diversified properties (Figure 4a). Especially the biomimetic skin-like material (VEH-MX-Gly) achieved by adding MXene (5 wt%) and glycol (15 wt%) has high stretchability, mechanical adaptability, conductivity, frost resistance, and ease of processing. It can be used as a data glove to recognize finger bending and transmit information (Figure 4c).

This method of starting from the powder and fusing it into a whole can also be regarded as a pre-treatment step to meet the basic requirements of coarse dispersion. Huang et al. proposed a kneading method that can quickly mix hydrophobic particles HPs with polyethylene imine (PEI) solutions to form "dough", which is beneficial for forming stable suspensions in aqueous solutions [33] (Figure 5a). Combined with PAM network, the composite hydrogel was obtained (Figure 5b), and the swelling ratio was reduced and the mechanical strength was significantly improved (Figure 5c), benefit from the introduction of HPs, such as polytetrafluoroethylene and silane treated SiO₂.

In addition to aiding in dispersion, the kneading process can also promote the entanglement of polymer chains and enhance the toughness of the material. Suo et al. mixed





lonic dough with a deep eutectic solvent [32]. (a) Formation of hydrogen bonding between ChCl and glycerol. Schematic proposed formation of the ionic dough. Preparation process of ionic dough. (b) Comparison of the ionic dough and traditional dough after being stored at 20 °C and 50%humidity for 20 days. (c) Lamb-shaped dough figurine used as a conductive medium to light up LED bulbs. (d) Photographs of the ionic dough and traditional dough before and after degradation in the soil. (e) Relative resistance variation as a function of a tensile strain from 0 to 150%. Schematic illustration of the ionic dough sensor attached to different parts for detecting human motions.

Figure 4



PAA/ACC based biomimetic skins [44]. (a) Schematics of the kneading method and the versatile design for biomimetic skins. (b) Photographs of kneading process by an automatic household dough maker for preparing VEH-CNT. (c) Photographs of a "data glove" mounted with the assembled skin-like sensors to perform a series of gestures. Relative resistance changes of skin-like sensors in response to sign languages.



Figure 5

Kneading-dough-inspired EI@HPs-PAM hydrogel [33]. (a) Photos of kneading HPs with PEI solution until smooth and sticky dough-like gel was achieved. (b) Scheme of preparing PEI@HPs/PAM hydrogel via UV irradiation or heating. (c) G' and G'' versus temperature (T = 20-80 °C) at a fixed strain ($\gamma = 1\%$) and a fixed frequency (f = 1 Hz).

Figure 6



Long-chain PEG hydrogel [45]. (a) Scheme for preparing hydrogel from dough. (b) Making hydrogels from preexisting polymers in two ways: a hydrogel from a solution of short chains and a hydrogel from a dough of long polymers. (c) The stress-stretch curves of the two hydrogels. (d) The highly entangled hydrogel differs from the short-chain hydrogel in various properties.

high molecular weight poly (ethylene glycol) (PEG) chains with a small amount of water and photoinitiator to form "dough", and homogenized the "dough" by repeatedly kneading and annealing at high temperature [45]. During the process, the crowded long polymer chains are first densely intertwined, then sparsely crosslinked into a network under ultraviolet light, and swell in water to reach equilibrium (Figure 6a). Compared with the hydrogel made from traditional solution of short chains, the gel made from "dough" of long chains has significantly improved in flexibility, toughness, strength and other mechanical properties (Figure 6d).

Materials based on self-assembly of surfactans in solid phase

Based on the movement of molecules in the solid phase, the powder can not only become a gel material, but also become a micro ordered macro continuous film by using surfactants. Molecular self-assembly is a ubiquitous phenomenon in nature and an important means of obtaining ordered molecular arrangement and creating new materials from the bottom up [46–52]. However,

Figure 7

traditional molecular self-assembly typically occurs in solution [53,54], and amorphous precipitates are usually obtained, in which the ordered regions of molecules are still at the micro/nano scale, unable to fully reflect the excellent performance of the material endowed by "assembly" [55–57].

Yan et al. proposed a solid-phase molecular self-assembly strategy, which utilizes amorphous precipitates formed by surfactants and negatively charged polymers (both molecules with self-assembly ability) to form a film under mild pressure and a small amount of water. Surfactants can form various structures such as micelles, vesicles, bilayers [58] and liquid crystals in solution, which have been studied very maturely [59,60]. By adding counter charged polyelectrolytes or polymers that can form hydrogen bonds with them, precipitation can be formed through bridging, dehydration, and other processes.

Research has confirmed [20,36] that the precipitation of surfactants and polyelectrolytes can spontaneously form continuous transparent films through solid-phase molecular self-assembly (Figure 7a). The molecules form a



(a) Schematic diagram of solid phase molecular self-assembly material preparation process [20]. (b) XRD patterns of the freeze-dried precipitate, condensed white cake, and transparent film [36]. (c) The influence of water ratio and cluster size or interparticle distance on fusion rate [61].

hexagonal or layered ordered arrangement, and the molecular arrangement becomes more orderly with increasing pressure. After the precipitation is completely dried, no matter how much pressure is applied, it is difficult to form a continuous transparent film (Figure 7b), indicating that trace amounts of water play an important role in promoting the diffusion of surfactant. On the other hand, if no pressure is applied to the newly prepared wet precipitate, it will not transform into a transparent film spontaneously, indicating that pressure is equally important. Theoretical calculations confirm [61] that both pressure and water significantly promote the diffusion of initial aggregates in precipitation (Figure 7c).

Factors affecting the structure of solid molecular selfassembly

Generally, longer hydrophobic chains facilitate the ordered assembly of surfactant bilayers in the film, while larger molecular weight polyelectrolytes facilitate the

Figure 8

long-range arrangement of surfactant bilayers and enhance the mechanical strength of the film. A study was conducted using polydiallyldimethylammonium chloride (PDDA) and sodium alkylsulfonate as model systems from both experimental and theoretical simulations [62]. The experiment found that the arrangement of sodium dodecyl sulfate (SDS) is more orderly than that of sodium decyl sulfate (SDeS), and it is difficult for sodium octyl sulfate (SOS) to form precipitates under the same conditions (Figure 8a). Meanwhile, as the molecular weight of PDDA increases, the tensile strength of the film gradually increases (Figure 8b). In addition, molecular dynamics simulations indicate that the persistent length of PDDA in the assembled structure increases as the hydrophobic chains of the surfactants get longer (Figure 8c). The Fourier transform images show that high molecular weight PDDA will be induced to orientation by the surfactant bilayer, indicating the formation of a large ordered structural domain (Figure 8d).



(a) FT-IR spectra for the PDDA-SDS and PDDA-SDeS films. (b) Mechanical test for the PDDA–SDS films of different PDDA molecular weights. (c) The relationship between alkyl sodium sulfate chain length and persistence length. (d) MD simulation results and the FFT reverse picture of SPMSA with the same surfactant SDS and varying the polymerization degree of PDDA [62].

In addition, the temperature of the mother liquor and the concentration of surfactants and polymers also have an impact on the assembly structure, similar to the selfassembly of molecules in solution. Moreover, external unidirectional squeezing force can induce the formation of oriented layered or hexagonal phases inside the film, endowing the material with anisotropy (Figure 9) [63].

Properties of solid-phase molecular self-assembly materials

Solid-phase molecular self-assembly materials have both hydrophilic and hydrophobic regions, allowing them to absorb non-polar substances and be responsive to water. Furthermore, both types of regions are present in the amorphous precipitates used for film formation, which allows many functional substances to be pre-dispersed in the precipitate through solution, resulting in better dispersion compared to kneading. These properties of the solid-phase molecular self-assembly materials lay the foundation for their promising application prospects.

Recyclable oil absorbing materials

Surfactants have hydrophobic tail chains, which result in corresponding hydrophobic regions in the solid-phase molecular self-assembly materials, accommodating nonpolar substances. Especially surfactants containing double tailed chains such as ditetradecyldimethylammonium bromide (DTTAB) can form larger hydrophobic regions, which can quickly (5 min) capture oil pollution through the principle of similar solubility (Figure 10b) [64]. It is worth mentioning that the pollution level and salt content of the water source do not have a significant negative impact on the oil absorption

Figure 9

capacity (Figure 10c), and even the oil absorption capacity in NaCl solution (237.1%) is slightly increased compared to pure water (220.0%). This is because NaCl can to some extent shield the electrostatic interaction between high molecules and surfactants, making the film structure relatively loose and not completely destroyed. Therefore, it has a wider application prospect and practical value in seawater with higher salt content. In addition, due to its regenerative ability, the oil absorption and oil removal cycle (Figure 10d).

Humidity drives the deformation of materials

Due to the presence of both hydrophilic and hydrophobic regions in the solid-phase self-assembled materials formed by the participation of surfactants, the film has a certain water absorption ability, and the diffusion rate of water on the surface and inside the film is different. The surface layer can rapidly undergo hydration, but the diffusion of water molecules within the film is hindered by the presence of a hydrophobic layer [35]. So, when the humidity on both sides of the film is different, a diffusion gradient of water will form inside, leading to the generation of tension. Therefore, the film can spontaneously deform and bend towards the dry side under humidity stimulation (Figure 11a) The higher the humidity on one side of the film, the greater the degree of deformation. By utilizing this property of the film, a self-driving skin humidity detector can be prepared. When the film comes into contact with the skin, it can undergo deformation by detecting water vapor on the skin surface (Figure 11b), without the need for external power supply, and also has the advantage of portability.



(a) 2D MAXS images, (b) 1D XRD pattern and (c) azimuthal angle plots of the films prepared via simple pressing after SPMSA strategy. (d) 2D MAXS images, (e) 1D XRD pattern and (f) azimuthal angle plots of the films prepared via unidirectional squeezing force after SPMSA strategy [63].



Figure 10

Solid phase molecular self-assembly DTTAB-PSS film oil absorbing material [64]. (a) The chemical structure of DTTAB and the chemical structure of PSS. (b) Photographs of the oil adsorption process using the DTTAB-PSS film. (c) Recycling test of the adsorption capacities of the DTTAB-PSS film for petroleum in DI water, 33 wt% NaCl solution, and dirty water containing much dust, respectively. (d) Schematic diagram of the procedure used to recycle the film for petroleum adsorption.

Figure 11



Solid phase molecular self-assembly SA-DTAB self-actuated deformation material [35]. (a) Schematic illustration of the mechanism of moisturedriven actuation. (b) Photos of the film bending against an approaching finger at a distance of a few millimeters. (c) The reversible bending behavior of the SA-DTAB film.

Meanwhile, this deformation is reversible and can therefore be reused (Figure 11c).

Moreover, after applying directional extrusion force, the hexagonal phase inside the film is arranged in a fixed direction, endowing the film with different mechanical properties in different directions, and always bending along the hexagonal phase axis after water absorption (Figure 12a) [63]. This is because the hydrophilic region expands more significantly, leading to a significant increase in interlayer distance (Figure 12b). On this basis, the two stacked films can be fused together by a small amount of water and mild pressure (Figure 12c). When there is a specific angle between their orientations, curling and helical deformation can be obtained (Figure 12d). When double-layer films with different offset angles are integrated side by side, more complex deformations can be observed (Figure 12e). And due to the inherent self-assembly ability of interface molecules, the two layers will automatically fuse together, endowing shape changing programmable materials with excellent fatigue resistance (Figure 12f).





Solid phase molecular self-assembly SA-DTAB Antifatigue Laminate Programmable Materials [63]. (a) Immediate bending of the films with different orientations when in contact with water. (b) Schematic illustration of anisotropic swelling of the film with oriented bilayers. (c) Schematic illustration of the fabrication procedure and 3D full-spectrum shape transitions behavior of the film (different colors are used to display the hexagonal structure with different orientations). (d) The geometry of ribbon models for various values of the two control parameters: the dimensionless width and the crossed angle. (e) Olympic rings and plant perversions formed with the ribbon motifs of different offset angles integrated side by side. (f) The pitch of the ribbons under multiple cycle test.

Anti-fatigue humidity sensor

Solid phase molecular self-assembly materials formed through electrostatic interactions have strong hygroscopicity and can be used as sensitive humidity sensors. Carbon nanotubes were deposited into solid-phase selfassembled thin films using co precipitation method, resulting in excellent conductivity (Figure 13a) [37]. Due to its conductivity derived from carbon nanotubes, the material is flexible and has good contact between carbon nanotubes at high humidity, resulting in excellent conductivity of the film. When the humidity decreases, the contact between carbon tubes is poor, the resistance increases, and the conductivity deteriorates (Figure 13c). Based on this, sensitive humidity sensors can be prepared, which can even distinguish different respiratory rates of the mouth and nose, and further distinguish the words or sentences spoken (Figure 13d). The output signal of the sensor is the rate of current change caused by humidity changes ($\Delta I/I_0$), which is not related to the area of the film. Therefore, when the film is damaged (such as the presence of holes with an area of 50%), the output signal is not affected, thus exhibiting characteristics of fatigue resistance and damage resistance.

Inducing regular folding of polymers

The structure of polymer chains is difficult to control in materials, resulting in many properties that cannot be developed. For example, polylysine (PLL) can only be applied in the field of degradable materials, but its



Figure 13

Solid phase molecular self-assembly DTAB-PSS-CNT-urea film humidity sensor [37]. (a) Schematic illustration of the fabrication procedure of the film. (b) Systematical illustration of the DTAB-PSS-CNT-urea film formation process. (c) Relationship between film conductivity (with and without CNTs) and storage humidity. (d) Response curves of mouth (upper panel) and nose (lower panel) with different breathing rates. Film is able to distinguish different words and sentences.

chirality cannot be utilized because the disordered chain conformation prevents the ordered arrangement of chiral centers, making it impossible to obtain the chirality of macroscopic materials. Due to the formation of a neatly arranged layered structure of amphiphilic oleic acid (OL) in solid-phase molecular self-assembly, each head group pairs with the counter charged polylysine head group, forcing the polylysine chain to undergo regular folding (Figure 14b), resulting in chirality [65]. Moreover, polylysine can achieve cluster luminescence (CTE) after aggregation, and the blue fluorescence immediately becomes circularly polarized light (CPL). The emission dissymmetric factor glum value can reach -0.016, providing new ideas for the development of circularly polarized luminescent materials. Furthermore, polylysine can transfer energy to sodium fluorescein (FS) dye molecules doped in films through Förster resonance energy transfer (FRET), and achieve chiral transfer (Figure 14c and d), emitting yellow circularly polarized light ($g_{lum} = -0.018$), providing the possibility for constructing multi-color circularly polarized luminescent materials.

Summary and outlooks

In this review, we summarized the construction methods of macroscopic continuous materials from powder based on solid-phase molecular motion, and analyzed the feasibility of the methods and the inherent self-healing property of the materials. This strategy reduces the use of harmful solvents and fully utilizes solid raw materials, in line with the development needs of low-carbon society and green chemistry. And it can also serve as a pre-treatment step to improve the dispersion or entanglement of internal materials, thereby enhancing material properties.





Solid phase molecular self-assembly PLL-OL circularly polarized luminescent materials [65]. (a) The schematic illustration of the solid phase molecular self-assembly of PLL-OL. (b) Chematic illustrations of PLL-OL self-assembled multilayer-ordered structure. (c) CPL spectra (Ex = 342 nm, FS: 0.87%) of PLL-OL film and PLL-OL \supset FS film. (d) Energy transfer and the generation of CPL via the FRET (Förster resonance energy transfer) between the CTE donor of PLL-OL film and the molecular acceptor FS.

Not only the methods based on dough and hydrogel are included, in particular, solid-phase molecular selfassembly method based on the precipitation formed by surfactants and polyelectrolytes is also introduced, from the principle to the unique structure and properties of the obtained materials. Firstly, the supramolecular film prepared by this method has both hydrophilic and hydrophobic microregions, providing the possibility for loading or doping multiple molecules and particles. Secondly, surfactants can form ordered arrangements through solid-phase molecular self-assembly, and even induce regular arrangements of polymers, improving the orderliness of the system and laying the foundation for the preparation of anisotropic films. Thirdly, noncovalent interactions reduce the resistance of molecular motion, making self-healing of materials possible.

Compared to starting from solution or melt, the uniformity of macroscopic continuous materials obtained from powder needs to be considered due to the limited migration ability of molecules in the solid phase. But it is also expected to obtain dynamically stable ordered structures, and even use this non-uniform structure at the micro or nanoscale to endow materials with new mechanical properties [66]. Although some work has demonstrated the auxiliary role played by pressure and small amounts of solvents in this process, there is still a lack of the most direct microscopic observation of solidphase molecular motion, limited by the interface hidden between two solids and the more complex molecular motion compared to the current research on solid surfaces.

Therefore, this method of utilizing molecular motion in the solid phase needs to be explored to obtain materials with better performance, and the mechanism needs to be further understood through the development of characterization techniques. This method is expected to become a new approach for developing macro continuous materials, improving resource utilization and reducing environmental hazards.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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