

Article

Particle Dynamics Study of Microstructural Evolution and Mechanical Response in Magnetorheological Fluids

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Abstract

Magnetorheological fluids (MRFs) exhibit field-dependent mechanical properties that are governed by the evolution of their internal particle structures. In this work, a particle-dynamics-based numerical method is used to investigate the microstructure formation and shear response of monodisperse and bidisperse MRFs at volume fractions of 22% and 33% under the same magnetic field and carrier-fluid viscosity. A mechanical model based on interparticle interactions is employed to describe particle motion and magnetic-field-induced chain assembly. To quantify the structural evolution during deformation, the average coordination number is introduced as a microstructural descriptor. The results show that bidisperse MRFs exhibit distinct chain formation mechanisms from monodisperse systems, particularly with decreasing particle size ratio and increasing concentration. Under steady shear, both systems display a fluctuating increase in stress, accompanied by structural rupture, migration and reorganization. However, concentration markedly affects the dominant evolution mode, while the incorporation of small particles in bidisperse systems weakens chain integrity, leading to stronger stress fluctuations and generally lower peak stress. These results provide insight into the coupling between microstructure evolution and mechanical response in MRFs.

Keywords: magnetorheological fluids; particle dynamics; microstructure evolution; shear response; bidisperse MRFs

1. Introduction

Magnetorheological fluid (MRF), first proposed in 1948, is a solid–liquid two-phase composite smart material formed by dispersing magnetizable particles in a carrier fluid [1,2]. Its macroscopic rheological properties are influenced by the internal microstructures induced under a magnetic field. In the absence of an external magnetic field, MRF behaves approximately as a conventional fluid; however, upon application of a magnetic field, it can reversibly transition into a semi-solid or solid state with high yield stress within milliseconds. Owing to its advantages such as high tunability, low energy consumption, wide operating temperature range, and excellent safety, MRF demonstrates broad application prospects in the aerospace field [3,4].

As aerospace products evolve toward lower costs, higher payload capacity, and long-term in-orbit operation, these demands have driven the development of spacecraft components with high-strength, low-density materials and thin-walled structures [5,6]. In



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traditional aerospace industrial manufacturing, components such as rudder surfaces, wing surfaces, propellant storage tanks for launch vehicles, as well as thin-walled revolving parts like cabins and end frames, are typically formed through milling processes [7,8]. These thin-walled structures are inherently complex [9], and their stiffness decreases as material is removed during processing. This necessitates dynamic adjustment of the clamping force applied by fixtures; excessive clamping force can lead to workpiece deformation, while insufficient force may fail to suppress cutting vibrations, thereby compromising the shaping and precision of the part. A flexible fixture system based on magnetorheological fluids can address this challenge by adjusting the coil current in real time to modify the magnetic field strength, thereby dynamically regulating the equivalent stiffness and damping characteristics of the clamping region. This enables the system to provide matched clamping force and damping support at different stages of the milling process, contributing to improved machining stability and accuracy.

MRFs are widely used in controllable transmission, damping, sealing, and precision actuation systems because they can rapidly transform from a liquid-like to a solid-like state under an applied magnetic field. In this field-induced solidification process, the shear yield stress is one of the most important macroscopic parameters, since it directly characterizes the load-bearing capacity and flow resistance of the structured suspension, and thus largely determines the performance limits of MRF-based devices. For this reason, the shear yield stress of MRFs has long been a central topic in both rheological characterization and engineering application studies. Early investigations mainly relied on experimental measurements. Dang et al. [10] measured the yield stress of MRFs in tubes using a pressure-driven device, where the critical pressure required to initiate flow under a magnetic field was converted into the corresponding yield stress. Wang and Gordaninejad [11] further examined the shear yield behavior of MRFs at high shear rates using a piston-driven rheometer, while Yang et al. [12] employed a parallel-plate rheometer to determine the static yield stress of ferrofluid-based magnetorheological fluids. These studies established the experimental foundation for yield-stress characterization under different loading modes and magnetic-field conditions. However, experimental determination of MRF yield stress generally requires dedicated apparatus, carefully prepared samples, and repeated calibration under coupled magnetic and mechanical loading, which makes the process time-consuming and resource-intensive, especially when a wide parametric space must be explored. Accordingly, particle-level simulation of field-induced load-bearing structures provides microscopic guidance for understanding the stiffness and damping regulation required in MRF-based aerospace fixtures and damping devices.

To overcome these limitations, increasing attention has been paid to numerical and theoretical approaches for predicting the shear yield stress of MRFs from their field-induced microstructures. Particle-level simulations have shown that yield behavior is strongly governed by the formation, interaction, and failure of chain or column structures. Ekwebelam and See [13] analyzed the static yielding behavior of bidisperse MRFs using particle dynamics simulations, and Kittipoomwong et al. [14] demonstrated that bidispersity can enhance the dynamic yield stress relative to monodisperse systems. Sherman and Wereley [15] further showed that particle size distribution plays a key role in determining the morphology of chain structures and the resulting stress response. On the modeling side, Li et al. [16] improved the classical single-chain model by considering the effects of magnetic field strength, interparticle spacing, and particle size, whereas Guo et al. [17] introduced an exponential distribution function to account for the angular deviation between particle chains and the external magnetic field, thereby improving the prediction of shear yield stress. More recently, Zhuang et al. [18] clarified the influence of carrier-fluid viscosity on the shear stress evolution under shear, and Peng and Pei [19] developed a mesoscopic particle-chain-based

model that quantitatively relates the total shear resistance to the resultant force carried by all chain structures in a unit area. Although these studies have significantly advanced the understanding of MRF yielding from the microstructural perspective, the coupling between microstructure evolution and macroscopic stress transmission remains insufficiently understood, particularly under conditions involving complex particle distributions, chain interactions, and multiparameter coupling. This still motivates the development of more physically grounded and computationally efficient models for yield-stress prediction.

Although previous studies have provided important insights into the yield behavior and microstructure of magnetorheological fluids, the correlation between microscopic structural evolution and macroscopic mechanical response under coupled magnetic-field and shear conditions has not yet been sufficiently clarified. To address this issue, the present work employs a particle-dynamics-based numerical framework to examine the formation and shear-induced evolution of particle-chain structures in magnetorheological fluids. The emphasis is placed on bidisperse systems, which are compared with monodisperse counterparts under the same magnetic-field strength, carrier-fluid viscosity, and particle concentration. By varying the particle-size ratio in the bidisperse systems, the role of small particles in chain formation, structural rearrangement, and stress transmission is analyzed under controlled conditions. The average coordination number is introduced to quantify the evolution of particle contacts during shear, and its variation is correlated with the transient shear-stress response. Through this analysis, the influence of bidispersity on chain integrity, structural reorganization, peak stress, and stress fluctuations is clarified at the particle scale. The results provide a more specific understanding of how particle-size distribution affects the shear response of magnetorheological fluids.

2. Methods and Validation

When magnetorheological fluid is subjected to a magnetic field of strength H , the magnetic moment m of a suspended particle can be expressed as [20]. This magnetic-moment expression is used under the low-field linear magnetization approximation, which is adopted here because the simulations use a fixed moderate magnetic field to compare structural and stress responses before explicitly considering saturation effects; strong-field cases would require a nonlinear magnetization law.

$$m = \frac{4}{3}\pi R^3 \chi H \quad (1)$$

where R represents the particle radius and χ denotes the effective particle magnetic susceptibility. Considering the additional magnetic field generated by the particle's magnetization, the expression for the magnetic force on particle i can be described using an enhanced dipole model [21],

$$\mathbf{F}^{mag} = -\frac{1}{2}\nabla U = -\frac{1}{2}\nabla(-\mathbf{m}_i \cdot \mu_0 \mathbf{H}_i) \quad (2)$$

where H_i represents the sum of the external magnetic field at particle i and the additional magnetic fields of the other particles, and μ_0 denotes the vacuum permeability.

To prevent overlap between moving particles, the soft repulsive force model is employed, with inter-particle friction neglected. The repulsive force is mathematically expressed as [15],

$$\mathbf{F}^{rep} = \sum_{j \neq i} F_0 \exp \left[-\beta \left(\frac{r_{ij}}{2R} - 1 \right) \right] \hat{\mathbf{r}}_{ij} \quad (3)$$

where β is the repulsive force coefficient, r_{ij} represents the distance between two particles, $\hat{\mathbf{r}}_{ij}$ denotes the unit vector along the interparticle direction, and F_0 is determined from force equilibrium calculations when particles are just in contact.

The viscous drag on a particle moving through a liquid is governed by the Stokes equations [22],

$$\mathbf{F}_i^{hyd} = -6\pi R\eta \mathbf{v}_i \quad (4)$$

where η represents the viscosity of the carrier fluid, and $\mathbf{v}_i$ denotes the velocity of the particle relative to it. Since the carrier fluid is stationary in this study, $\mathbf{v}_i$ is simply the particle's velocity. The dynamical equation of the particles can be expressed as,

$$\begin{cases} m a_x = \frac{d^2 u}{dt^2} = \Sigma (F_x^{mag} + F_x^{rep}) + F_x^{hyd} \\ m a_y = \frac{d^2 v}{dt^2} = \Sigma (F_y^{mag} + F_y^{rep}) + F_y^{hyd} \end{cases} \quad (5)$$

The velocity-verlet algorithm used in the study is illustrated in Figure 1 for computation and the iterative process. The velocity at the next half time step is calculated based on the current acceleration,

$$\mathbf{u}(t + 0.5\Delta t) = \mathbf{u}(t) + 0.5\mathbf{a}(t) \cdot \Delta t \quad (6)$$

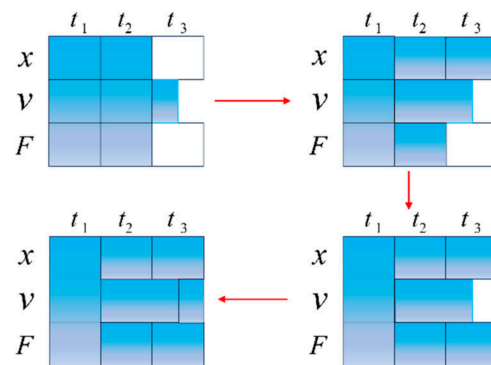


Figure 1. Schematic diagram of velocity-verlet calculation principle.

In the second step, the particle position is calculated using the velocity at the next half-time step,

$$\mathbf{x}(t + \Delta t) = \mathbf{x}(t) + \mathbf{u}(t + 0.5\Delta t) \cdot \Delta t \quad (7)$$

Finally, the acceleration is calculated from the position of the next time step and the velocity of the next time step is calculated from the acceleration,

$$\mathbf{u}(t + \Delta t) = \mathbf{u}(t + 0.5\Delta t) + 0.5\mathbf{a}(t + \Delta t) \cdot \Delta t \quad (8)$$

Because the force evaluation and motion update of each particle can be performed locally once the relevant neighboring interactions are identified, these two procedures are treated as independent computational tasks. Taking advantage of this spatial locality, a domain-decomposed parallel strategy is adopted to improve computational efficiency. As shown in Figure 1, the magnetic interaction force between two particles depends strongly on their relative orientation with respect to the applied magnetic field. Specifically, the force decreases as the angle between the center-to-center line and the magnetic-field direction increases, reaching its maximum and minimum when the two directions are parallel and perpendicular, respectively, thus exhibiting a symmetric angular dependence. In addition, the magnetic interaction decays rapidly with increasing interparticle distance; as shown in Figure 2, the force becomes very weak at large separations and is nearly negligible when the distance exceeds $6R$. Therefore, the contribution of distant particles to the motion of a target particle can be reasonably ignored. Based on this short-range

interaction characteristic, a neighbor-list method is introduced to reduce the computational cost. As illustrated in Figure 3, the computational domain is divided into a set of grids, and particles are assigned to the corresponding cells. During the force calculation, only particles located in neighboring grids are considered, which significantly improves the efficiency of the simulation.

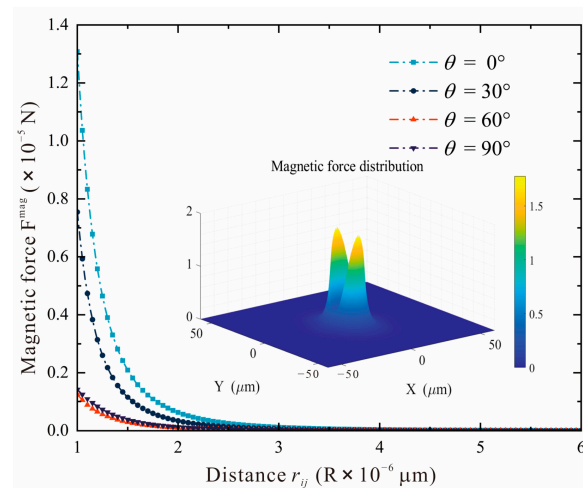


Figure 2. The curve of magnetic force variation with distance.

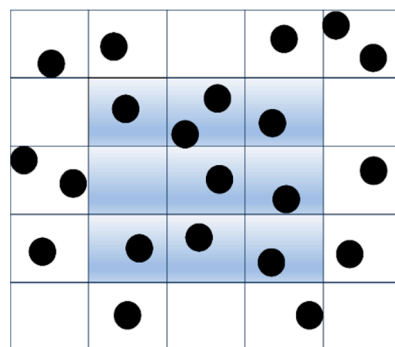


Figure 3. Neighborhood list method schematic.

The computational domain is a two-dimensional region of dimensions $L \times W$, with the width oriented along the y-direction and the magnetic field applied in the positive y-axis direction. To simplify the complexity of the force calculation module, fixed particles identical to those in the interior are arranged along the upper and lower boundaries. These fixed particles serve as substitutes for boundary condition calculations when interior particles come into contact with the upper and lower boundaries, while periodic boundary conditions are imposed on the left and right sides. In this two-dimensional configuration, the volume fraction is converted to an area fraction, and the calculated number of particles is rounded up to the nearest integer. The corresponding particle concentrations become 11%, 22%, and 33%. In practical engineering applications, the response time of magnetorheological fluids is generally on the order of milliseconds. Therefore, the internal state of the magnetorheological fluid at 2 ms after the application of an external magnetic field is considered the steady state. The parameters employed in the simulation are presented in Table 1. This two-dimensional approximation reduces computational cost and makes particle rearrangement easier to resolve, but the particle concentration is therefore an equivalent area fraction rather than a true three-dimensional volume fraction.

Table 1. Simulation parameters.

Parameter	Parameter Value
η , Pa·s	0.1
T , K	298
χ	1.0
R , μm	10
μ_0 , H/m	$4\pi \times 10^{-7}$
ρ , Kg/m ³	7.86×10^3
H , A/m	63,680

To provide a preliminary check of the program reliability, the condition corresponding to Figure 4a in the reference was considered, with a particle volume fraction of 30% and a particle radius of 5 μm , while the other parameters were kept the same as those reported in the literature [22]. Under this condition, the simulated particle distribution shows the formation of chain-like and locally aggregated structures along the magnetic-field direction, which is generally consistent with the microstructure characteristics reported in the reference. This agreement suggests that the present program can reasonably capture the basic evolution features of particle chaining and aggregation in magnetorheological fluids.

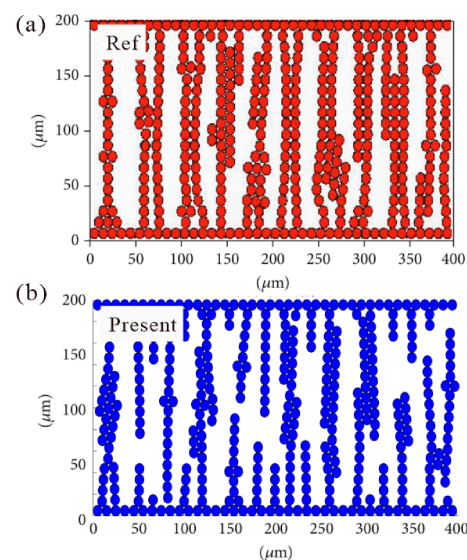


Figure 4. Internal structures of monodisperse magnetorheological fluid used for model validation: (a) Results in Ref; (b) Present results.

3. Results and Discussion

Under an applied external magnetic field, particles experience magnetic forces and form chain-like structures aligned along the direction of the magnetic field. As illustrated in Figure 5, at a magnetic field strength of 63,680 A/m, relatively well-defined chain structures are formed within the system at volume fractions of 22% and 33%. However, the increased viscosity of the carrier fluid at these concentrations leads to greater viscous resistance during particle migration and reorganization, thereby hindering this process. Consequently, at a concentration of 22%, a considerable number of free (isolated) particles remain in the internal structure under steady-state conditions. Nevertheless, as the concentration increases to 33%, the reduced interparticle spacing not only enhances the magnetic force acting on the particles but also shortens the migration and reorganization pathways. This results in fewer free particles in the formed structure compared to the case with 22% concentration. Furthermore, owing to the increased volume fraction, the number of particles

within the effective range of magnetic interaction ($6R$) rises, leading to the formation of more intricate chain structures. The magnetic field is the primary factor governing the magnitude of interparticle magnetic attraction and the stability of the field-induced structures. Under the low-field linear approximation, the magnetic moment is proportional to H , and the magnetic interaction therefore increases approximately with H^2 . A stronger field would be expected to accelerate particle aggregation, increase the compactness and connectivity of chain or bundle structures, and enhance the stress level under shear. In the present work, H is kept constant so that the effects of concentration and particle-size distribution can be isolated and compared under the same magnetic condition.

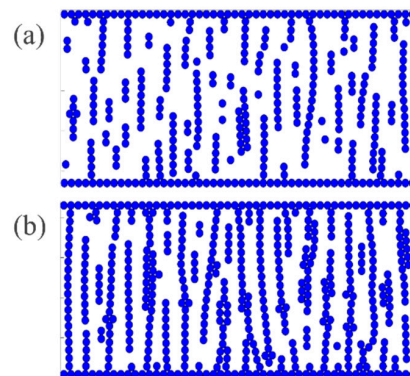


Figure 5. Internal structures of monodisperse magnetorheological fluids under steady-state conditions: (a) 22%; (b) 33%.

Based on the monodisperse magnetorheological fluid, the total volume fraction is kept constant, with small particles accounting for 20% of the total volume fraction. The size ratios λ of the added small particles to the large particles are 0.9, 0.7, and 0.6, respectively. As shown in Figure 6, which illustrates the internal structure under steady-state conditions, it can be observed that in bidisperse magnetorheological fluids, small particles also participate in chain formation. Moreover, as the size ratio decreases, the increase in the number of small particles gradually shifts the particle system towards a multi-particle system. During the chain formation process, multiple particles tend to participate simultaneously, rather than merely extending the end-to-end length of chain structures. Therefore, compared to the simple chain structures in monodisperse magnetorheological fluids, the evolution direction of chain structures in bidisperse magnetorheological fluids becomes increasingly complex as the size ratio decreases.

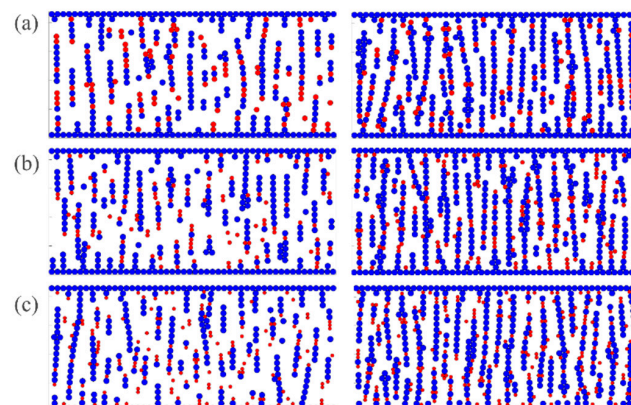


Figure 6. Internal structures of bidisperse magnetorheological fluids under steady-state conditions, with the left column corresponding to 22% and the right column to 33%: (a) $\lambda = 0.9$; (b) $\lambda = 0.7$; (c) $\lambda = 0.6$.

Furthermore, at a particle size ratio of 0.9, the formed microstructures are still close to those of the nearly monodisperse case, since the size difference between the two types of particles is relatively small. As the size ratio decreases, the structural role of the small particles gradually changes. At relatively high size ratios, small particles can still be incorporated into the chain structures together with large particles. In contrast, at lower size ratios, the large particles increasingly dominate the formation of the main chain skeleton, while the small particles tend to occupy the interstitial spaces and attach to the outer regions of the chains. This transition in chain organization is clearly illustrated in Figure 7.

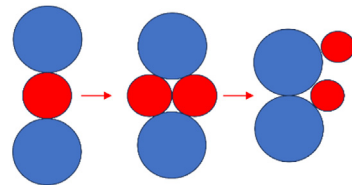


Figure 7. Transition in chain formation mode.

As the particle concentration increases, the average interparticle distance decreases, which promotes the formation of increasingly complex and compact chain-like structures under an external magnetic field. In such cases, the internal microstructure of magnetorheological fluids becomes much denser, and the overall mechanical response can no longer be accurately represented by conventional single-chain or double-chain models. To address this issue, the present study calculates the stress response of monodisperse and bidisperse magnetorheological fluids under steady shear by explicitly resolving the displacement and force acting on each particle in the flow field. In this manner, the macroscopic rheological behavior is directly correlated with the underlying microscopic particle interactions and structural evolution. In addition, the average coordination number is introduced as a quantitative parameter to characterize the evolution of the internal structure under shear.

As illustrated in Figure 8, the flow of the magnetorheological fluid is characterized by a steady Couette-flow profile, and the carrier-fluid velocity is expressed in terms of the shear rate as follows,

$$v = \dot{\gamma} y e_x \quad (9)$$

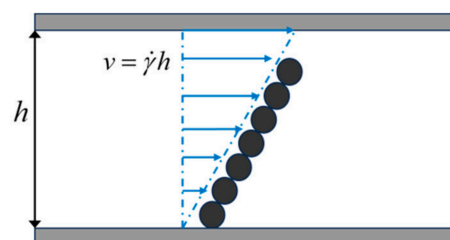


Figure 8. Schematic diagram of Couette flow.

At this point, a shear is applied horizontally to the right with shear rates of 20 s^{-1} , 40 s^{-1} , and 50 s^{-1} . For the prescribed Couette-flow background, the particle-level contribution to the internal stress is evaluated using the following stress tensor τ ,

$$\tau = -\frac{1}{V} \sum_{i=1}^N (F_i \cdot e_x) \left(y_i - \frac{h}{2} \right) \quad (10)$$

where V represents the volume, which in a two-dimensional case can be expressed as $L \times W$, F_i denotes the horizontal component of the resultant non-hydrodynamic interaction

force acting on particle i under shear, y_i is the y -coordinate of the center of particle i , and h is the height of the computational domain in which the shear is applied. More specifically, V is the equivalent two-dimensional domain measure, h is the height over which shear is imposed, y_i is the y -coordinate of particle i , and the force term is the horizontal component of the resultant non-hydrodynamic particle interaction force used to evaluate the equivalent shear stress.

As the concentration increases, the interparticle distance decreases, leading to progressively complex chain structures formed by particles suspended in the carrier fluid under an applied magnetic field. This complexity intensifies with increasing concentration, resulting in denser internal chain architectures. Conventional single-chain and double-chain models are insufficient to accurately capture the overall mechanical response. Therefore, by examining the displacement and force acting on individual particles within the shear flow field, the stress response of monodisperse and bidisperse magnetorheological fluids under steady-state shear conditions was calculated. From the perspective of microscopic particle interactions, the relationship between the microstructure and macroscopic rheological properties was established. Moreover, the average coordination number was introduced to visualize the structural evolution under shear flow. The governing equation can be expressed as,

$$CN = \frac{1}{N} \sum_{i=1}^N H_i \begin{cases} H=1 & r_{ij} \leq 2R + \delta \\ H=0 & r_{ij} > 2R + \delta \end{cases} \quad (11)$$

where δ represents the thickness of the surfactant layer on the particle surface. Under the influence of a magnetic field, interparticle interaction forces cause the particles to come into contact with one another, forming chain-like structures aligned along the direction of the external magnetic field. In the coordination-number calculation, two particles i and j are regarded as being in contact when $r_{ij} \leq R_i + R_j + 2\delta$, where δ is the surface-layer thickness of each particle; δ is set to $0.01R$ in the present simulations.

At the initial stage, in the absence of an external magnetic field, the particles are randomly dispersed in the carrier fluid, as shown in Figure 9a, and direct contacts between particles are rarely observed. Accordingly, the average coordination number is close to zero. It should be noted, however, that a few particles may still come into incidental contact because of the initial spatial distribution, and therefore the average coordination number is not strictly zero in the numerical results. Once the external magnetic field is applied, particles gradually approach each other and form chain-like structures aligned with the field direction, leading to an increase in the average coordination number. Owing to differences in particle concentration, magnetic field strength, and the resulting interparticle interactions, the formed chain structures can exhibit different morphological characteristics, which are reflected by different values of the average coordination number. In general, a larger average coordination number indicates that more particles are in contact with their neighbors, corresponding to a more complex internal structure, as illustrated in Figure 9b,c.

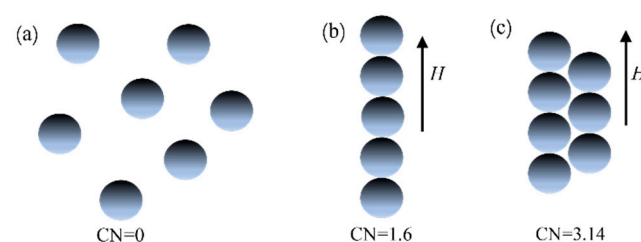


Figure 9. Schematic diagram of the average coordination number principle: (a) random distribution; (b) single-chain structure; (c) double-chain structure.

As shown in Figure 10, the stress–strain curves at different imposed shear rates exhibit an overall fluctuating upward trend in the steady-state regime. The corresponding microstructures at different shear rates are presented in Figure 11. It can be seen that, as shearing proceeds, the carrier fluid continuously interacts with the field-induced chain structures. With increasing shear rate, the chains become more inclined with respect to the magnetic-field direction, which increases the resultant force component in the shear direction and therefore leads to a higher macroscopic stress.

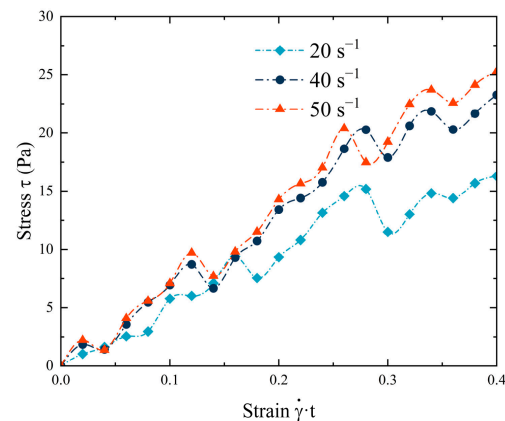


Figure 10. Stress–strain curve at a volume fraction of 22%.

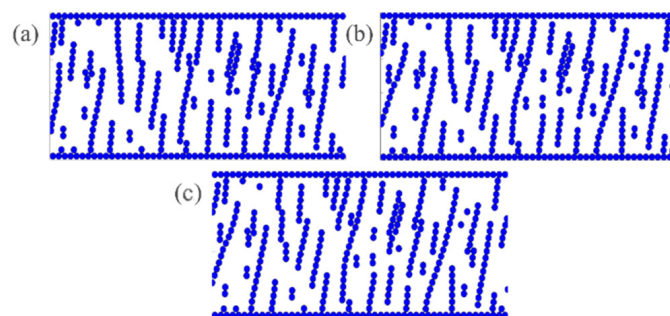


Figure 11. Internal structure at a volume fraction of 22% under different shear rates: (a) 20 s^{-1} ; (b) 40 s^{-1} ; (c) 50 s^{-1} .

The structural evolution during shearing further explains this stress behavior. As shown in Figure 11, the average coordination number first decreases rapidly and then increases with noticeable fluctuations, indicating a complex structural reorganization process at this concentration. At the initial stage of shear, weak connections within the chain structures are broken, resulting in a reduction in the coordination number. As the deformation proceeds, however, the broken chain segments and dispersed particles gradually reattach to neighboring structures and merge into longer and thicker chain bundles or columnar aggregates. In addition, as discussed in the previous structural analysis, a considerable number of free structures are present at a concentration of 22% under steady-state magnetic conditions. Under the action of shear, these structures undergo further rearrangement and participate in the formation of coarser load-bearing networks, as reflected by the average coordination number variation in Figure 12. The development of these elongated and thickened structures enhances the overall resistance to shear, and consequently the stress response shows an overall fluctuating increase.

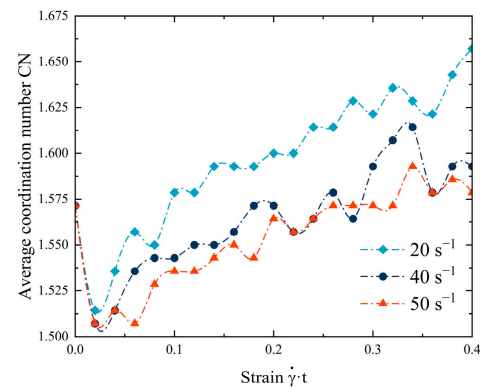


Figure 12. Average coordination number variation curve during the shearing process at a volume fraction of 22%.

When the particle concentration is further increased to 33%, the stress evolution under the applied shear flow is shown in Figure 13. Similar to the case with a volume fraction of 22%, the stress still exhibits an overall increasing trend, but the peak stress reaches a significantly higher level. This difference is closely related to the change in the initial microstructure at high concentration. As indicated by the microstructural analysis, the interparticle distance is further reduced at a volume fraction of 33%, and the particles no longer form relatively isolated chain structures under the external magnetic field. Instead, a more complex chain-network structure is established, with an initial average coordination number of approximately 2.7, as shown in Figure 14.

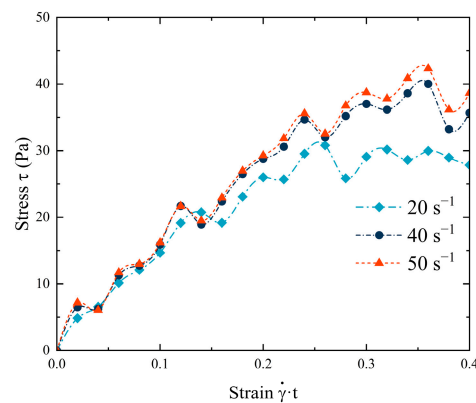


Figure 13. Stress–strain curve at a volume fraction of 33%.

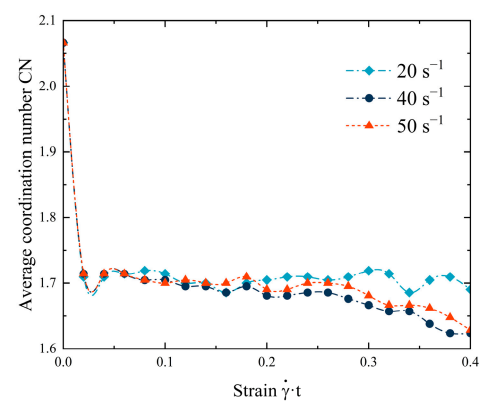


Figure 14. Average coordination number variation curve during the shearing process at a volume fraction of 33%.

However, the structural evolution during shearing is markedly different from that observed at a volume fraction of 22%. As the shear proceeds, the average coordination number decreases continuously from about 2.7 to 1.7, showing a sustained monotonic decline. This behavior indicates that the initially formed network structure is progressively disrupted by the applied shear. As the network breaks down, the fragmented chain segments are convected and redistributed under the action of the hydrodynamic drag force. Therefore, although the stress response remains at a relatively high level because of the initially dense structure, the microstructural evolution is dominated by continuous structural damage rather than shear-induced reconstruction.

As can be inferred from Figures 13–15, part of the initially formed double-chain and thick-chain structures are separated into single-chain structures under shear. Under the high-concentration condition, however, the interparticle distance is extremely small, and the number of free short chains and isolated particles is very limited. Consequently, the internal chain structures are highly compact, making it difficult for the shear flow to induce effective structural reorganization; instead, its dominant effect is structural disruption. Although some weak connection points within the network may break during shearing, the overall framework of the internal structure remains largely preserved, allowing the system to sustain a considerable stress response. The continuous increase in stress during shear is therefore mainly attributed to the lateral magnetic support among densely packed neighboring chains, together with the load-bearing capability of particles within the long-chain structures. This result indicates that the chain-network structure formed at high particle concentrations possesses strong resistance to shear deformation. In the selected strain window, the high-concentration network mainly evolves through local rupture, thinning, and partial loss of interchain connections, while its overall framework remains compact. Therefore, the structural change at 33% volume fraction is more appropriately evaluated together with the stress response and the coordination-number evolution rather than from instantaneous morphology alone.

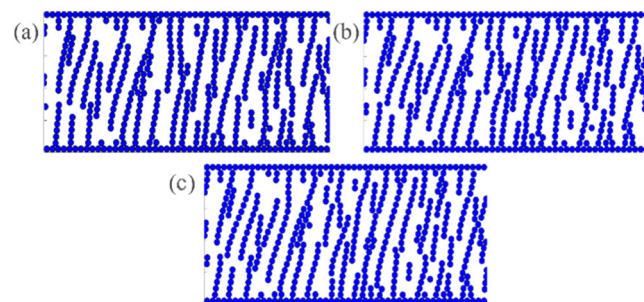


Figure 15. Internal structure at a volume fraction of 33% under different shear rates: (a) 20 s^{-1} ; (b) 40 s^{-1} ; (c) 50 s^{-1} .

The stress response curves of bidisperse magnetorheological fluids under applied shear are presented in Figures 16 and 17. By comparison with the corresponding results for monodisperse systems shown in Figures 10 and 13, it can be seen that both bidisperse and monodisperse magnetorheological fluids exhibit an overall fluctuating increase in stress during shearing. However, the bidisperse systems show more pronounced stress fluctuations and generally lower peak stress values than the monodisperse ones. In addition, the peak stress tends to decrease as the particle size ratio decreases. An exception is observed at a volume fraction of 33%, where the peak stress at a size ratio of 0.6 is slightly higher than those at size ratios of 0.9 and 0.7. The difference in stress scale between monodisperse and bidisperse systems is concentration-dependent: at 22%, replacing part of the large particles with smaller particles more strongly weakens continuous load-bearing

paths, whereas at 33% the denser contact network partly compensates for weaker small-particle magnetic contacts, so the stress levels in Figures 13 and 17 remain of the same order.

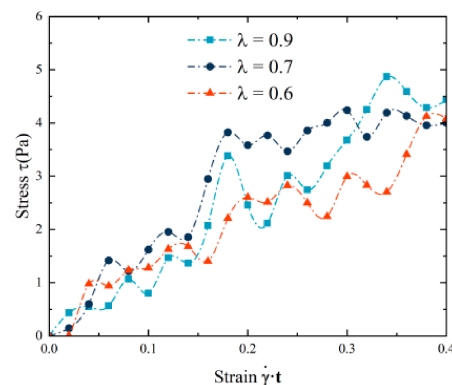


Figure 16. Stress response curve of bidisperse magnetorheological fluid at a volume fraction of 22%.

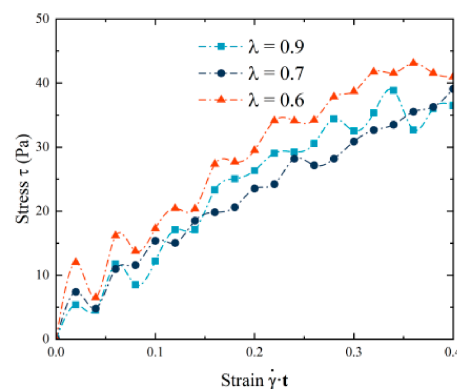


Figure 17. Stress response curve of bidisperse magnetorheological fluid at a volume fraction of 33%.

To interpret this behavior, Figure 18 shows the variation in magnetic interaction force with interparticle distance for particles of different sizes. The peak stress is not only affected by structural factors such as chain length, the number of particles involved in chain formation, and the amount of chain structures formed, but also by the strength of the magnetic connections between particles within the chains. Stronger interparticle interactions lead to tighter particle connections, which make the chain structures more resistant to separation under shear and thus improve their load-bearing capacity. As discussed previously, in bidisperse magnetorheological fluids, small particles mainly participate in chain formation by being embedded between large particles or by pairing with other small particles. Since the magnetic interaction force decreases with decreasing particle size ratio, as shown in Figure 18, the resulting chain structures become weaker than those in monodisperse systems composed entirely of large particles. Consequently, the bidisperse fluids generally exhibit lower peak stress under shear. The relatively higher peak stress observed at a size ratio of 0.6 and a volume fraction of 33% suggests that, under this condition, the specific packing and structural organization of particles may partially compensate for the reduced pairwise magnetic interaction.

Figure 19 shows the structural evolution of bidisperse magnetorheological fluids during shear. At a volume fraction of 22%, the chain structures first break at their weak connection points under the applied shear. As the deformation proceeds, the broken segments further undergo shear-induced reorganization through interaction with the surrounding free structures. Owing to the participation of small particles in chain formation and their relatively weaker magnetic interactions, the connections associated with small

particles are mechanically more fragile and therefore more susceptible to rupture under shear. This feature contributes to the more pronounced stress fluctuations observed in bidisperse magnetorheological fluids at both 22% and 33% volume fractions.

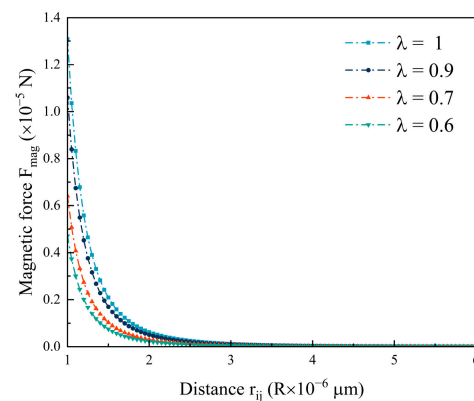


Figure 18. Decay curves of magnetic force with distance under different particle size ratios.

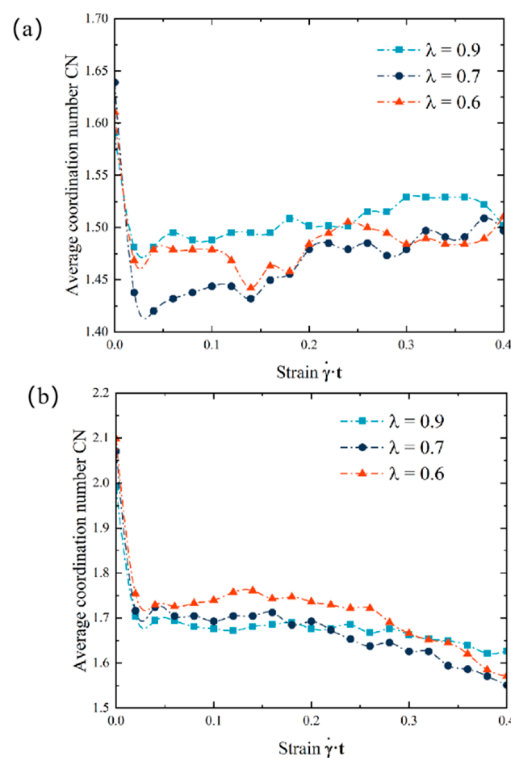


Figure 19. Average coordination number variation curves of bidisperse magnetorheological fluid: (a) volume fraction of 22%; (b) volume fraction of 33%.

At a volume fraction of 33%, structural destruction still dominates the shear-induced evolution of the bidisperse system. However, for the case with a particle size ratio of 0.6, the number of configurations in which small particles are enclosed between neighboring large particles becomes higher, which enhances the integrity of the chain structures and improves their resistance to shear. Meanwhile, the small particles are gradually compressed and constrained by the surrounding large particles, promoting additional lateral contacts and increasing the local structural complexity, eventually leading to the formation of chain-bundle structures, as shown in Figure 20. Compared with isolated single-chain structures, these chain bundles allow more particles to participate collectively in bearing the shear load. As a result, the peak stress response under this condition is higher than that corresponding

to particle size ratios of 0.7 and 0.9. This indicates that, at high concentration, $\lambda = 0.6$ does not simply weaken the bidisperse system; the increased number of small particles can provide additional bridging and filling sites between large-particle chains, enhancing local packing and lateral force transmission despite the weaker individual magnetic interaction of small particles.

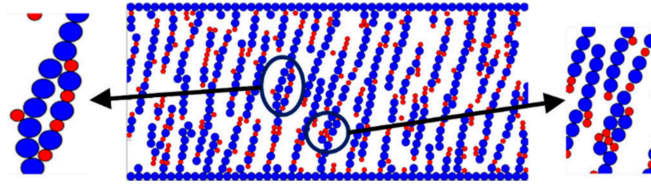


Figure 20. Internal structure at peak stress for a particle size ratio of 0.6 at a volume fraction of 33%.

4. Conclusions

This work comparatively investigated the microstructural characteristics of monodisperse and bidisperse magnetorheological fluids at volume fractions of 22% and 33%. The results show that, as the particle concentration increases, the interparticle distance decreases, which strengthens the magnetic interaction and shortens the characteristic distance for particle migration and structural rearrangement, thereby promoting the formation of denser and more complex chain-like structures. For bidisperse magnetorheological fluids, the chain formation mechanism of the small particles changes progressively with increasing concentration and decreasing particle size ratio, leading to distinct structural organization features compared with those of monodisperse systems. Furthermore, steady shear was imposed to examine the relationship between microstructure evolution and stress response in both monodisperse and bidisperse fluids. It was found that the stress generally exhibits a fluctuating upward trend during shearing, which is closely associated with the combined effects of structural migration, reorganization, and rupture at weak connection points. Compared with monodisperse fluids, the participation of small particles in chain formation weakens the structural integrity of bidisperse systems, resulting in more pronounced stress fluctuations and lower peak stress under shear. These conclusions are subject to the assumptions of two-dimensional particle dynamics, prescribed Couette flow, and low-field linear magnetization; future work will consider nonlinear magnetization, larger three-dimensional particle ensembles, and systematic variation in magnetic-field strength.

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