

SHEAR THICKENING FLUIDS FOR BALLISTIC TEXTILE APPLICATIONS: MECHANISMS, PERFORMANCE, AND LIMITATIONS

¹VISHAL S K

¹Dr B R Ambedkar NIT Jalandhar, India

Vishal S K: skvishalsdm@gmail.com

Corresponding author: VISHAL S K

ABSTRACT

Shear thickening fluids (STFs) have attracted considerable attention for improving the impact resistance of flexible textile-based ballistic protection systems. These non-Newtonian suspensions show an increase in resistance to deformation when subjected to high shear rates while maintaining a relatively low resistance under slow deformation. This behavior provides an opportunity to modify the mechanical response of high-performance fabrics without completely sacrificing their flexibility and conformability. This review examines the application of STFs in ballistic textile systems, with particular emphasis on their rheological behavior, mechanisms of shear thickening, interaction with textile structures, and influence on ballistic performance. The principal mechanisms associated with shear thickening, including order–disorder transition, hydroclustering, and jamming, are discussed in relation to particle concentration, interparticle interactions, and applied shear conditions. The effects of STF treatment on yarn mobility, inter-yarn friction, energy absorption, and projectile resistance are also considered, particularly for high-performance fibers such as Kevlar and ultra-high molecular weight polyethylene (UHMWPE). In addition, the review addresses practical limitations associated with STF-treated fabrics, including increased areal density, changes in flexibility, particle agglomeration, environmental sensitivity, and the dependence of performance on impact conditions. The challenges of maintaining effective shear-thickening behavior during high-rate and ballistic loading receive particular attention. Finally, current research gaps and potential approaches for improving STF stability, textile integration, and ballistic performance are discussed. The review provides an overview of the opportunities and limitations of STF-treated textiles for the development of lightweight and flexible ballistic protection systems.

KEYWORDS: Shear thickening fluid (STF), Hydro-clustering, jamming, agglomeration

1. SHEAR-THICKENING FLUIDS

The development of lightweight and flexible ballistic protection is becoming an important research area, as conventional rigid armor systems can impose significant penalties in terms of weight, mobility, and wearer comfort. High-performance textile fibers such as Kevlar and ultra-high molecular weight polyethylene (UHMWPE) are widely investigated for soft armor because of their high specific strength and energy absorption capability. However, the ballistic performance of textile structures is influenced not only by the intrinsic properties of the fibers but also by yarn mobility, friction between adjacent yarns, fabric architecture, and the manner in which load is transferred through the textile during impact. One way to change these properties is to add shear thickening fluids (STFs) to textile structures. STFs are concentrated suspensions of solid particles dispersed in a liquid medium that exhibit a strong increase in viscosity when subjected to sufficiently high shear rates. Under low-rate deformation, the suspension can flow relatively easily, whereas the resistance to deformation increases substantially when the applied shear exceeds a critical condition. This behavior is associated with changes in particle interactions and microstructure within the suspension.

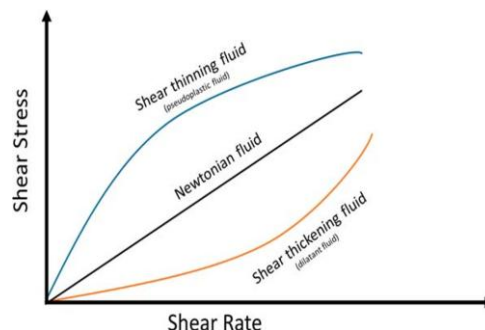


Figure 1: Shear rate to shear stress

When an STF is incorporated into a textile, the resulting response is governed by the interaction between the fluid, particles, and fiber network. The increased resistance of the STF during rapid deformation can restrict relative movement between yarns and alter the way stresses are distributed through the fabric. An increase in inter-yarn friction can also reduce yarn slippage and fiber pull-out, which may contribute to improved energy dissipation and ballistic resistance (Ribeiro et al., 2022). Unlike permanently rigid reinforcements, the fluid-based nature of STF treatment provides the possibility of retaining

a substantial degree of textile flexibility under normal conditions. The performance of STF-treated fabrics, however, is not determined by shear thickening alone. Parameters such as particle size and concentration, carrier-fluid properties, particle–particle interactions, fabric construction, STF impregnation level, and loading rate can significantly influence the response of the composite textile. The mechanisms responsible for shear thickening have also been described using different models, including order–disorder transitions, hydroclustering, and stress-induced jamming. Understanding the relationship between these mechanisms and the deformation of textile structures is therefore essential for interpreting reported ballistic performance. Although numerous studies have demonstrated improvements in the impact resistance of STF-treated fabrics, the reported performance varies considerably between material systems and test conditions. Differences in STF formulation, fabric type, projectile characteristics, impact velocity, and experimental configuration can produce substantially different results. In addition, issues such as increased fabric mass, reduced flexibility, particle agglomeration, environmental stability, and the response of STF-treated textiles under very high-rate loading remain important barriers to practical implementation.

Accordingly, this review focuses on the mechanisms, processing approaches, ballistic performance, and limitations of STF-treated textile systems. Particular emphasis is placed on relating the underlying shear-thickening mechanisms to textile deformation and ballistic response, comparing reported performance across different STF formulations and fabric systems, and identifying the factors responsible for variations between published results. The review also discusses current limitations and potential strategies for improving the stability and effectiveness of STF-based flexible ballistic protection.

2. MECHANISM OF NON-NEWTONIAN FLUIDS

The unusual rheological behavior of shear thickening fluids (STFs) is the main aspect that makes them work in ballistic and impact-resistant applications. When they are exposed to high shear rates or quick deformation, their viscosity suddenly and reversibly increases. This happens because of the interaction between suspended particles and the fluid around them in complicated ways that change over time when stress is applied. When an outside force is applied to the suspension, the microstructure goes from being free-flowing to being constrained or jammed. This makes the fluid act like a solid for a short time. This change makes the system better at taking in and releasing kinetic energy, which is why STFs are ideal for flexible protective composites. Many theoretical frameworks have been proposed over the years to explain this behavior, each focusing on different microscopic interactions that lead to the viscosity jump. The most well-known of these are the order-disorder transition, hydro-clustering, and fluid-structure interaction or jamming mechanisms. In modern perspectives, the order-disorder transition is regarded not as an independent mechanism but as a precursor to cluster formation and jamming. These models work together to help us understand how the way particles are arranged, hydrodynamic forces, and interactions with structural materials affect the impact-resistant performance of systems that use STF (Chen et al., 2016).

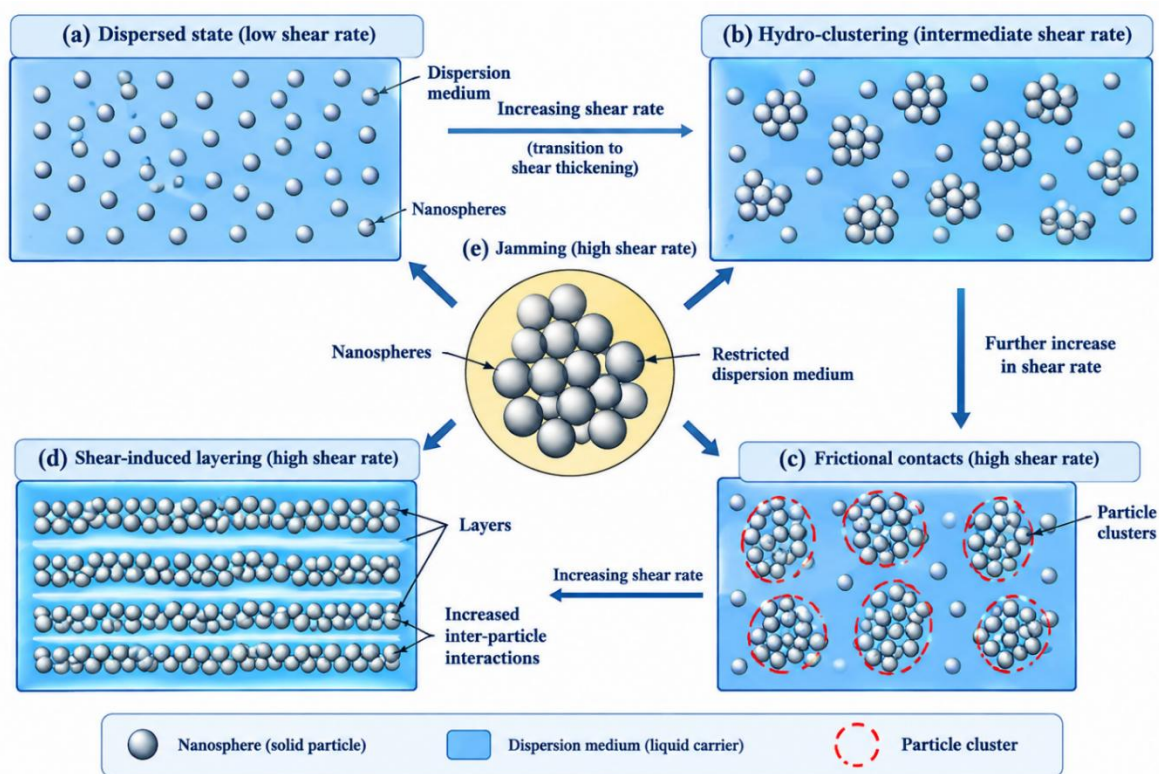


Figure 3: Evolution of structures with increasing shear time (a) equilibrium, (b) buildup of the structure, (c) formation of clusters, (d) changes in clusters after a long time of shearing, (e) free disperse medium and restrained disperse medium.

3. ORDER-DISORDER TRANSITION MECHANISM

Hoffman came up with the first explanation for shear thickening in colloidal suspensions. It is called the order-disorder transition theory. This model says that when shear rates are low, particles in a concentrated suspension line up in an ordered, layered structure. This shape lets them slide past each other easily, which makes the viscosity low. But when the shear rate goes above a certain level, this ordered arrangement falls apart and becomes random or disordered. When the particles change their alignment, the hydrodynamic interactions and flow resistance increase quickly, which causes the viscosity to rise quickly. Diffraction tests show a clear periodic pattern that is typical of ordered layering when the shear rate is below the critical level. When the threshold is crossed, the diffraction rings disappear, which means that the particles are moving and are not aligned in a specific direction (Hoffman, 1972). Further rheological and scattering investigations demonstrated that this structural disintegration is directly associated with the onset of shear thickening.

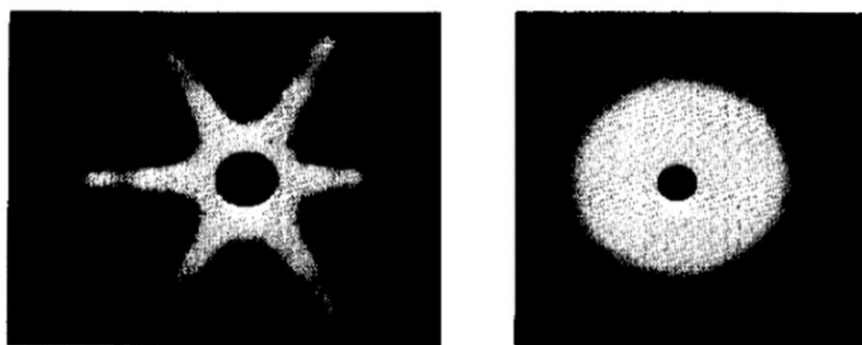


Figure 4: Diffraction patterns before and after shear thickening (Hoffman, 1972)

At relatively low shear rates, concentrated particles can adopt an ordered or partially layered configuration in which their relative motion is accommodated by the carrier fluid. As the applied shear rate approaches the critical shear-thickening region, this ordered arrangement becomes unstable, and particles are displaced from their preferred layers. The resulting disordered configuration increases hydrodynamic resistance and contributes to the increase in apparent viscosity. This concept is known as the order-disorder transition (ODT).

Laun et al. found that as the number of suspended particles grew, the line between order and disorder became clearer and sharper. Later, computer models like Stokesian dynamics showed that the transition is affected by the concentration of particles and the forces that lubricate particles that are close to one another. Lubrication films cannot maintain stable flow when the spaces between particles shrink. This causes the particles to move unpredictably, disrupts order, and increases viscosity rapidly. This theory demonstrates that small changes in the particle network can thicken the material on a larger scale. The level of order depends on how the particles are distributed, the surface chemistry, and the polarity of the solvent. For instance, silica nanoparticles combined with polyethylene glycol display noticeable changes from order to disorder due to strong hydrogen bonding and controlled steric repulsion. In contrast, mixtures that use polymers change more gradually. This mechanism explains how shear-thickening fluids (STFs) stay fluid in protective textiles, even when they are bent slightly, so that yarns can move freely. But when something hits or stabs the fluid suddenly, the disorder in the microstructure becomes much worse, turning the fluid into a solid-like matrix that holds the yarns together.

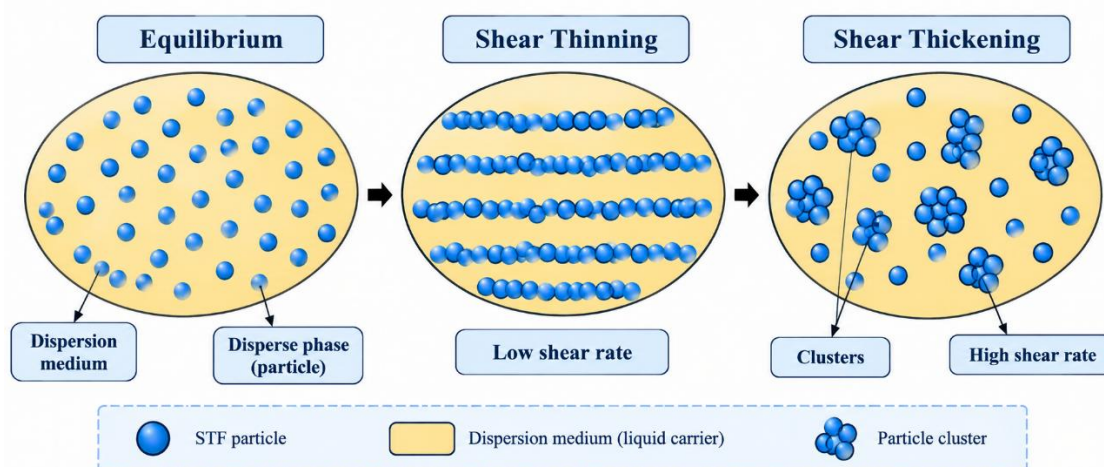


Figure 5: Order-Disorder Theory

However, ODT should not be presented as the universal or sole origin of shear thickening. Experimental and theoretical studies have shown that significant thickening can occur without a clearly identifiable order–disorder transition. Therefore, ODT is best regarded as a description of one aspect of particle rearrangement rather than a complete explanation of DST.

4. HYDRO-CLUSTERING MECHANISM

Researchers discovered that not all shear-thickening behaviors stem from order–disorder transitions in prior studies. With a further increase in shear, hydrodynamic interactions between neighboring particles become increasingly important. The flow generates lubrication forces that drive particles into transient, particle-rich regions known as hydro-clusters. Within these clusters, particle mobility is restricted, and the carrier liquid must flow through increasingly constrained regions; consequently, hydrodynamic resistance and apparent viscosity increase.

Hydro-clustering is particularly useful for describing continuous shear thickening, where viscosity increases progressively with increasing shear rate. Importantly, the clusters are dynamic rather than necessarily permanent solid structures; they form and break as the imposed shear changes. Thus, hydro-clustering provides a bridge between the relatively mobile particle state at lower shear and the strongly constrained state reached at higher stress. Brady and Bossis came up with the hydro-clustering mechanism, which helps us understand better. It implies that at elevated shear rates, short-range hydrodynamic lubrication forces aggregate particles, surpassing the typically weak electrostatic or steric repulsion that maintains their separation. After these repulsive barriers are crossed, particles temporarily come together to form dense, short-lived groups called hydro-clusters. These clusters hold onto the liquid around them and make the effective volume fraction of solids in the suspension higher, which makes the viscosity much higher (Brown E et al., 2014).

Fast confocal microscopy and light scattering were used in visualization studies to show that hydro-clusters form when something thickens. Cheng et al. took pictures of moving clusters in silica–glycerin suspensions and linked their appearance to the start of thickening. Maranzano et al. showed that changing the chemistry of the surface of particles affects the intensity of thickening by changing the balance between hydrodynamic attraction and surface repulsion. The strength and length of these clusters depend on the concentration of particles, the ratio of their length to their width, and the roughness of their surfaces. When clusters become closer to each other, the interaction happens between them, which makes the fluid less mobile and causes discontinuous shear thickening (DST), resulting in the viscosity varying a lot.

The hydro-clustering mechanism is a very important mechanism for fabrics treated with STF to work as ballistic armors. When a projectile hits the fabric, it causes the fibers to move apart in areas of high shear. This makes the particles in these areas come together rapidly, creating hydro-clusters in less than a second. This process makes the liquid thicker and shifts the weight from one yarn to the next. The yarn stays in place and spreads the impact energy sideways because it acts like a solid for a short time. When the stress is removed, the clusters break up, and the fluid returns to its original low-viscosity state, which keeps it flexible. The hydro-clustering model is now believed to be the primary reason why the majority of STFs utilizing silica or polymers continue to increase in thickness. It can accurately predict how materials will behave in systems with more than one phase or in systems with nano-reinforced materials, where hybrid particles like SiC or graphene change how fluids interact with one another. The process of forming and breaking down hydro-clusters is like a tiny switch that changes how materials behave, making them act like a solid or a liquid. This has a direct effect on how well the STF absorbs and spreads out energy from impacts.

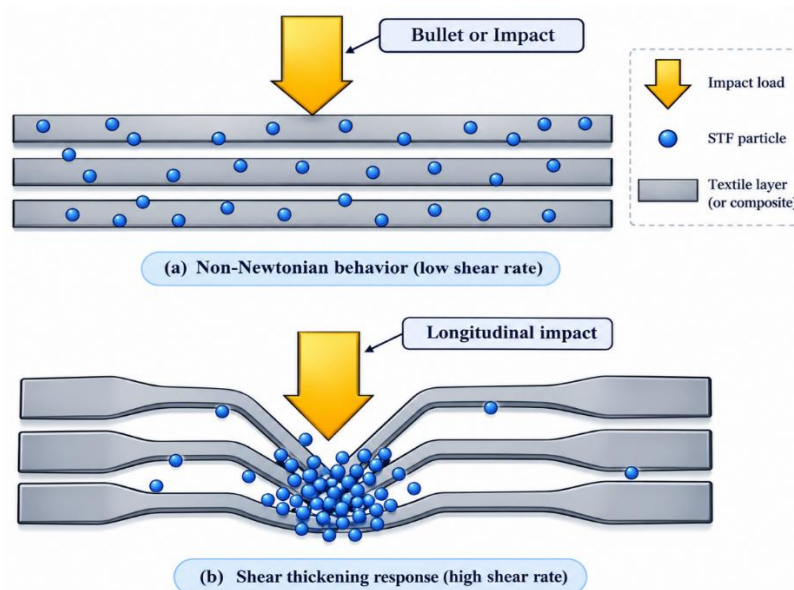


Figure 6: Shear thickening fluid during impact in protective textiles

5. FLUID-STRUCTURE INTERACTION AND JAMMING MECHANISM

The study by Chen et al. (2024) examines how the rheology of shear-thickening fluid (STF) interacts with structural deformation. It clarifies the shear-thickening mechanism. In this mechanism, the STF is an active part of a composite network. This network interacts dynamically with its supporting matrix, such as foam or fabric. When the structure and STF collide, they move against each other. This movement creates localized high-shear areas that thicken the fluid. This interaction changes the composite from being soft to being able to support weight and absorb significant kinetic energy. Drop-weight experiments with STF-filled foams showed a three-stage response, including a viscous damping phase followed by a rapid thickening phase, where the fluid stiffens and s-ballistic energy is absorbed. (Ribeiro et al., 2022) 92molecular weight polyethylene (UHMWPE) has shown 92ed. Numerical simulations using the coupled Euler-Lagrange method confirmed that changes in STF viscosity over time and position during impact are key for understanding the energy absorption. Near the impact point, viscosity increases quickly, forming jammed zones that prevent local deformation. The areas around these zones stayed fluid, allowing stress to spread. This viscosity gradient balances rigidity and flexibility, reducing peak impact forces and extending loading time.

The research also revealed that STF operates similarly to the jamming mechanism. When densely packed particles are compressed and sheared, they create a network that temporarily halts the fluid's movement. This network behaves like a solid and stops flow until the stress is lifted, at which point it becomes fluid again. The combination of foam compression and STF jamming produces a cushioning effect that outperforms regular high-viscosity fluids. The ability to switch between jammed and unjammed states enables the object to endure multiple impacts without permanent damage. This fluid-structure interaction explains how STF-based composites dissipate energy through viscous damping, structural deformation, and localized solidification. The findings suggest that adjusting the size, concentration, and viscosity of the STF formulation, along with the porosity or stiffness of the host matrix, can enhance energy absorption. This integration of rheology and structure marks the next step in STF research. It moves beyond fluid mechanics to develop armor systems that can adjust to various impact conditions.

6. APPLICATION OF SHEAR-THICKENING FLUID IN BALLISTIC PROTECTION

The above rheological mechanisms become important in STF-treated textiles because the STF is confined within and between the yarns. Under low or moderate loading, the STF allows relative yarn movement and therefore preserves the flexibility of the textile. When an impact generates sufficiently high local shear, particle interactions intensify, and the STF becomes substantially more resistant to deformation. This response increases resistance to relative yarn movement and can increase inter-yarn friction, thereby restricting yarn pull-out and promoting load transfer to neighboring yarns.

The contribution of the STF, however, depends strongly on the impact regime. At relatively low impact velocities, the increased inter-yarn friction and restricted yarn mobility can substantially improve energy absorption. At high velocities, the response is more complicated because the STF-treated fabric can constrain yarn movement and modify the failure mode. For example, Lu et al. reported that at approximately 500 m/s, STF-treated aramid fabrics exhibited a transition toward shear-dominated failure and reduced yarn pull-out, which resulted in lower specific energy absorption than the corresponding untreated fabrics under their particular test conditions. Therefore, it would be incorrect to state that increasing impact velocity simply produces progressively better STF performance. The dominant mechanism should consequently be discussed in terms of shear stress, particle concentration, particle interactions, and impact timescale rather than impact velocity alone. Impact velocity determines the severity and rate of loading, but the actual STF response also depends on formulation and fabric architecture.

Shear thickening fluids, or STFs, are mixtures that don't follow Newton's laws of viscosity. They contain silica nanoparticles suspended in a liquid, like polyethylene glycol. They thicken quickly when put under a lot of stress. This means that when you move them normally, they behave like liquids. But when they hit something rigid they act like solids. This property makes them suitable for flexible ballistic protection. The work demonstrates how to evenly distribute particles and polymers while strengthening their interactions. The main goals are to increase particle size, modify surfaces, and enhance mixing methods. When processing is stable, sedimentation doesn't occur, and shear response improves. The study also explores how soaking fabrics like Kevlar and UHMWPE in STF increases their energy absorption and impact resistance. When the yarns bond better, it's easier to distribute loads, and they are less likely to pull out upon impact. STF-treated materials remain flexible and provide substantial protection, addressing the issue of armor being too stiff. Hydro-clusters form when an object strikes the fluid. These are crucial for ballistic resistance. Hydro-clusters help keep the yarn from moving and distribute energy over a larger area. The study reveals that better results can be obtained by altering particle shapes, using hybrid or multiphase fillers, and improving rheological properties for enhanced performance during high-speed impacts. STF composites can be used to create lightweight, flexible ballistic protective fabrics suitable for various applications. (Zhang et al., 2021)

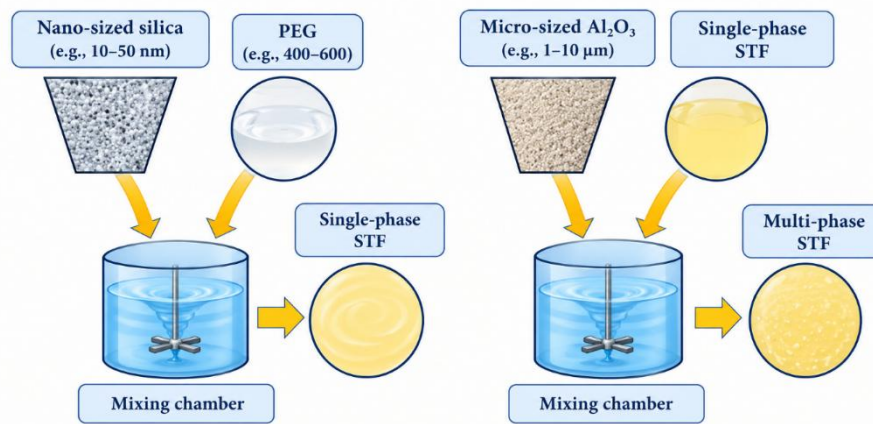


Figure 7: Single- and Multi-phase Shear-Thickening Fluid

STFs make it easier for yarn to interlock, help force move through particle interactions, and create a dense, semi-solid network when they hit something. This process happens without making the material much less flexible when it is worn normally. Gurgen et al. (2017) applied both single-phase and multi-phase shear-thickening fluids (STFs) containing silica and silicon carbide (SiC) particles in polyethylene glycol to Twaron fabrics. Adding SiC, which is known for its hardness, helped the treated fabrics spread and absorb impact energy better by increasing the friction between the yarns and the surface. The results showed that thickening behavior is not the only protective factor; the higher particle density and contact interactions in multi-phase STFs also create stronger force transfer networks upon impact. Because of these findings, fabrics that were treated with these STFs absorbed up to 96% more energy and had shallower trauma depths than fabrics that were not treated or were treated with only one phase STF (Gürgeç & Kuşhan, 2017).

STFs make ballistic protection a lot better at low to medium speeds by making the yarn stick together better and spreading out the energy of the impact. But they don't work as well when the projectiles are moving quickly. Long et al. (2025) examined the dynamic response of shear-thickening fluids (STFs) composed of silica nanoparticles suspended in polyethylene glycol (PEG) at projectile velocities exceeding those commonly evaluated in low-speed conditions. The principal conclusion is that at elevated strain rates, the protective efficacy of STFs diminishes due to insufficient time for the fluid to completely thicken and exhibit solid-like behavior. When shear rates are moderate, STFs become a lot thicker, which makes it difficult for things to pass through them. But this effect becomes less important as the speed of the impact goes up. Therefore the length of the impact and the strain rate are very important for STFs to work well. This limit happens because the shear thickening process needs enough time for particles to come together and make a temporary solid network. The study indicates that STFs need better particle types, concentration, and carrier fluid viscosity to improve response time and energy absorption for effective high-speed ballistic protection. By combining these optimized STFs with high-performance fabrics like aramids or UHMWPE, it is possible to make flexible, lightweight armor systems that protect against a wider range of impact speeds (Long et al., 2025).

A study examining the ballistic performance of Kevlar fabric infused with a shear thickening fluid (STF) via a fluid-structure interaction (FSI) numerical simulation, employing the Arbitrary Lagrangian-Eulerian (S-ALE) algorithm, revealed that STF-Kevlar composite fabric exhibits markedly superior impact resistance compared to unmodified Kevlar. The ballistic limit (V50) for pure Kevlar was 55.14 m/s, but the STF-Kevlar composite had a much higher limit of 72.40 m/s. The numerical simulation method took into account the STF's unique viscosity function and predicted a V50 of 70.40 m/s for the composite, which is only 2.8% off. The numbers indicated that the STF makes the fabric less likely to change shape when it hits something, making it more resistant to projectiles than neat Kevlar. The STF-Kevlar composite depended more on the STF to absorb energy as the speed of the impact went up. The energy absorption test indicated that most of the projectile's kinetic energy changes into the internal energy of the STF-Kevlar system. This phenomenon is different from neat Kevlar, which mostly absorbs energy through friction between the yarns. This validated FSI numerical simulation presents an innovative method for forecasting and enhancing the ballistic performance of STF-Kevlar in engineering applications, thereby obviating the necessity for prefabricated composite fabric samples (Zhihao et al., 2023).

The study conducted by Bajya et al. (2022) investigated the improvement in protection efficiency of ultra-high molecular weight polyethylene (UHMWPE) woven fabrics using shear thickening fluid (STF) treatment. The STF was produced with silica nanoparticles that were 100 nm, 300 nm, and 500 nm in size and mixed with polyethylene glycol (PEG 200) at a solid fraction of 0.65 w/w. Ethanol was added to help the particles mix properly. A full factorial design enhanced the fabric impregnation process by examining three variables, including the dimensions of the silica particles, the STF dilution ratio (1:4, 1:6, 1:8), and the padding pressure (2, 4, 6 bar). Rheological tests showed that the shear-thickening behavior is not steady; instead, larger particles cause wider shear-thickening plateaus. We used a 20 kg dart at 4.5 m/s (200 J) for low-velocity dynamic impact testing (ASTM D3763) and 9 mm bullets at 430 m/s for ballistic testing (NIJ 0101.06). The ANOVA test revealed that both the dilution ratio and padding pressure had a significant effect on the STF add-on, but only the dilution ratio had an effect on energy absorption. Fabrics that had STF added to them (16–34%) absorbed 35–79% more impact

energy than fabrics that didn't have it added. This happened because the yarns rubbed against each other more and bent in a way that made them stronger during impacts. We made ballistic soft armor panels (SAPs) with the same areal density (4.5 kg/m^2) in three different ways: 30 layers of neat fabric (W30), 25 layers of STF-treated fabric (S25), and a mix of 11 unidirectional (UD) laminates and 12 STF-treated layers (U11 + S12). The hybrid U11 + S12 panel was able to stop bullets with an average back face signature (BFS) of about 30 mm, which is the same as panels made entirely of UD laminates. SEM tests showed that the nanoparticles were spread out evenly and that the fibers in STF-treated samples had more friction. This caused less yarn pull-out and localized catastrophic failure instead of more widespread deformation. The results indicated that UHMWPE fabrics treated with STF soak up more energy and can take the place of some of the heavier UD laminate layers without losing their ability to protect against bullets. This change makes them both more flexible and less expensive (Bajya et al., 2022).

Table 1: Results of shear thickening test

Performance Metric	Untreated Fabric	Optimized STF-treated Fabric	Improvement
STF Add-on (wt%)	-	15–25%	-
Low-Velocity Impact Energy Absorption	100 J	135–150 J	35–79%
Ballistic Limit (V_{50})	~190 m/s	~240 m/s	26%
Flexibility (Bending Modulus)	-	10–15% stiffer	Moderate trade-off

Neelanchali et al. (2018) studied how effective the Shear Thickening Fluid (STF) treatment is for improving the impact resistance of Ultra High Molecular Weight Polyethylene (UHMWPE) composites. Their study used both low-velocity drop tower testing and high-strain-rate Split Hopkinson Pressure Bar (SHPB) testing. It showed that the performance of STF-treated UHMWPE depends heavily on the strain rate applied and how the STF is incorporated into the ballistic material. In low-velocity impact tests (2 to 4 m/s), the strain rate for the composite was below 10 s^{-1} , which is lower than the STF's critical shear rate (CSR) of 15.3 s^{-1} . Because the shear-thickening phenomenon wasn't fully activated, adding STF in this scenario did not improve the penetration resistance or the overall energy absorption of the composite panels compared to untreated panels. This indicates a limitation for STF-treated armor under low-energy, non-ballistic threats. The study assessed three different STF treatment methods under high-strain-rate conditions:

- Method 1 (STF in a Weak Medium): When weak, foamed polymeric sheets absorbed STF and were placed between UHMWPE layers, the composite structure failed quickly. This resulted in very low specimen stress (16.16 MPa) compared to neat UHMWPE (318 MPa). This indicates that a weak carrying material will break before the stress pulse is fully transferred, which reduces the potential benefit of the STF.
- Method 2 (Liquid STF Pouch): When a layer of pure liquid STF was placed between two UHMWPE specimens, the stress pulse was transmitted, and the STF showed its shear-thickening property. This contributed up to 90 MPa of specimen stress. Even though the overall composite still performed worse than neat material (318 MPa), it demonstrated that STF needs to be in its pure fluid state or embedded in a supportive material to activate its protective properties.
- Method 3 (STF Impregnation): When UHMWPE specimens were impregnated with STF through dipping and then dried, the specimens showed improved impact resistance. The peak specimen stress for the STF-impregnated UHMWPE was higher than that of the neat, untreated material at most tested loading rates. This led to the conclusion that STF's impact-resisting efficiency is best when integrated into a strong fabric through impregnation, with performance increasing as the loading rate rises.

The coating of a non-Newtonian fluid made from silica nanoparticles (nanofiller) and polyethylene glycol (carrier fluid) improved the protective performance of traditional plain woven Twaron fabric used in body armor. The non-Newtonian polymer also displayed excellent shock absorption, as shown in a drop weight test, and added about 20% in weight. Using this treated composite fabric with a non-Newtonian fluid would greatly benefit the protective performance-to-weight ratio of conventional body armors made of high-performance fibers. It could also help reduce blunt trauma behind armor during ballistic impacts due to better yarn-to-yarn stability in the treated composite fabric, as seen in the yarn pulling-out test.

The yarn pull-out test indicated that the force needed to pull a yarn from the non-Newtonian fluid-treated fabric is four times greater than that of the untreated fabric. This is due to the extra non-Newtonian polymer layer on the treated fabric's surface and the friction between yarns, which limits the movement of the fibers and yarns. A much higher load is necessary to overcome resistance from adjacent fibers and the covered polymer layer when pulling out a yarn from the treated fabric. The yarn-gripping effect of the treated fabric increased because of the inter-yarn friction force in the Twaron fabric treated with the non-Newtonian polymer compared to the untreated fabric. While the increased weight and thickness of Twaron fabric impregnated with the non-Newtonian polymer raise bending rigidity, the increased interactions among fibres and yarns caused by the polymer enhance their resilience during bending. This leads to slightly decreased bending rigidity and

bending hysteresis. Overall, the change in bending rigidity and bending hysteresis is minimal between the untreated and treated fabrics. The flexibility of the Twaron fabric treated with a non-Newtonian polymer remains unchanged.

7. LIMITATIONS AND FUTURE PERSPECTIVES OF STF-TREATED TEXTILES

Although shear thickening fluid (STF) treatment can improve the impact resistance of textile structures, its effectiveness depends strongly on the STF formulation, particle characteristics, processing conditions, fabric architecture, and impact velocity. Therefore, the use of STFs in ballistic textiles involves several trade-offs between impact resistance, areal density, flexibility, durability, and performance under different loading conditions. Reviews of STF-treated ballistic fabrics have also highlighted the large variation in experimental conditions reported in the literature, making direct comparison between different studies difficult (Ribeiro et al., 2022).

(I) INCREASED MASS AND REDUCED FLEXIBILITY

The addition of STF introduces both the liquid carrier and solid particles into the textile structure, which increases the mass of the treated fabric. Although STF treatment can increase impact energy absorption, excessive STF add-on can reduce the flexibility and drape of the textiles. Majumdar et al. (2014) investigated the effects of silica concentration and padding pressure on Kevlar–STF composites and showed that processing conditions significantly influence STF add-on and impact energy absorption. Their study reported an increase in impact performance of up to approximately 400% after STF treatment, while higher padding pressure reduced STF add-on and simultaneously increased impact energy absorption. These results demonstrate that simply increasing the amount of STF retained by the fabric is not necessarily the optimum approach; the STF add-on and processing conditions must be optimized together (Majumdar et al., 2014).

(II) PARTICLE SIZE AND DISPERSION

The size of the dispersed particles also has a significant influence on the behavior of STF-treated fabrics. Lee et al. (2009) compared silica particles with average diameters of 100, 300, and 500 nm in silica colloidal suspensions. The fabric treated with the 100 nm particles showed better impact energy absorption and resistance to blunt trauma than fabrics containing the larger particles and the untreated fabric under the investigated conditions. The smaller-particle suspension also produced the largest increase in inter-yarn friction at the onset of shear thickening. However, the authors also observed earlier failure of primary yarns in the impacted region under fully clamped boundary conditions, demonstrating that particle size and fabric boundary conditions can strongly influence the final ballistic response (Lee et al., 2009).

The concentration of nanoparticles must also be carefully controlled. Khodadadi et al. (2019) investigated Kevlar fabrics impregnated with nanosilica/PEG STFs containing 15, 25, 35, and 45 wt.% silica. Their results showed that the STF concentration affected the ballistic response and energy absorption of the treated fabric, with the 35 wt.% formulation providing the highest reported specific energy absorption among the investigated formulations. The results indicate that increasing particle concentration does not necessarily produce a continuous improvement in ballistic performance, and an optimum concentration may exist for a particular textile and STF system (Khodadadi et al., 2019).

(III) HIGH-VELOCITY IMPACT LIMITATIONS

STF treatment should not be assumed to provide the same level of protection at all impact velocities. Lu et al. (2019) examined neat and STF-impregnated aramid fabric panels at impact velocities of approximately 500 m/s. For their single-ply and 10-ply panels, the specific energy absorption of the STF-treated fabrics was 44.8% and 64.1% lower, respectively, than that of the corresponding untreated fabrics. The authors attributed this behavior to the restriction of primary-yarn movement caused by the STF, which changed the dominant failure mechanism from tensile failure toward shear failure, promoted earlier yarn damage, and reduced yarn pull-out. Therefore, the ballistic advantage of STF treatment depends strongly on the impact regime and fabric configuration, and STF treatment should not be considered universally beneficial at very high projectile velocities (Lu et al., 2019).

This result is particularly important when comparing V_{50} values reported in different studies. Differences in V_{50} should not be interpreted solely as differences in STF effectiveness because projectile type, impact velocity range, fabric type, number of plies, boundary conditions, STF formulation, and STF add-on can all influence the measured response. Ribeiro et al. (2022) therefore emphasized the need for more homogeneous ballistic testing conditions when comparing STF-treated fabrics from different studies.

Temperature sensitivity. The rheological behavior of an STF and the friction generated between adjacent yarns can also change with temperature. Li et al. (2020) investigated silica-based STFs prepared using different dispersing media over the temperature range of 20–50°C. They found that the dispersing medium strongly influenced the temperature dependence of the STF/Kevlar system. At 50°C, formulations containing dispersing media with longer molecular chains or more hydroxyl groups retained substantially more inter-yarn friction than the formulation based on 1,3-propanediol. In the reported comparison, the retained friction was approximately 60% for the more suitable dispersing media, whereas only approximately 11% remained for the 1,3-propanediol-based system. These results demonstrate that temperature stability depends not only on the silica concentration but also on the chemical structure of the carrier liquid (Li et al., 2020).

(IV) LIMITATIONS ASSOCIATED WITH THE STF FORMULATION

The carrier liquid, particle concentration, particle size, and particle–fluid interactions must therefore be considered simultaneously when designing an STF for ballistic textiles. Lee et al. (2009) demonstrated the influence of particle size on inter-yarn friction and ballistic response, while Khodadadi et al. (2019) demonstrated that silica concentration affects the ballistic performance of Kevlar–STF systems. Consequently, there is no single STF formulation that can be expected to provide optimum performance for all textile systems and impact conditions (Lee et al., 2009; Khodadadi et al., 2019).

(V) MULTI-PHASE STF SYSTEMS

An alternative approach to improving the performance of STF-treated textiles is the use of multi-phase formulations. Gürgen and Kuşhan (2018) investigated aramid fabrics impregnated with multi-phase STFs containing carbide additives. They reported that STF treatment increased inter-yarn friction, while the carbide phase provided an additional energy-absorption mechanism. However, the carbide additives also disrupted the shear-thickening behavior of the STF. This demonstrates the trade-off associated with introducing a second particle phase: additional energy-absorption mechanisms may be obtained, but the rheological response of the STF can also be altered (Gürgen & Kuşhan, 2018).

8. FUTURE RESEARCH DIRECTIONS

Future research should therefore focus on optimizing the complete STF–textile system rather than maximizing shear thickening alone. Particle concentration, particle size, carrier-fluid chemistry, STF add-on, fabric architecture, and impact velocity should be investigated systematically because each parameter can alter the balance between flexibility and impact resistance. Studies should also report the areal density of both untreated and STF-treated fabrics so that improvements in ballistic performance can be evaluated on a weight-normalized basis.

Hybrid and multi-phase particle systems are promising because they can introduce additional energy-absorption mechanisms while modifying the rheological response of the STF. However, the results of Gürgen and Kuşhan (2018) indicate that secondary particles can also disrupt shear thickening. Therefore, future work should optimize the concentration, size, morphology, and compatibility of the secondary phase rather than assuming that adding another particle type will automatically improve ballistic performance (Gürgen & Kuşhan, 2018).

Particle surface modification and improved dispersion control are also important research directions. Since particle size and concentration influence inter-yarn friction and ballistic response, controlling particle–fluid interactions may provide a way to obtain a strong shear-thickening response while minimizing particle agglomeration and processing difficulties (Lee et al., 2009; Khodadadi et al., 2019).

Environmental and durability testing should receive greater attention. Li et al. (2020) demonstrated that temperature can significantly modify the frictional behavior of STF-treated Kevlar fabrics. Future studies should therefore investigate repeated temperature cycling, humidity exposure, prolonged storage, bending, folding, abrasion, and repeated impact to determine whether the STF retains its rheological and ballistic properties during service (Li et al., 2020).

Finally, future studies should use more consistent ballistic test conditions and report the STF composition, particle size, particle concentration, carrier-fluid properties, STF add-on, fabric areal density, number of plies, projectile type, impact velocity, and boundary conditions. Reporting mean $\pm$ standard deviation and the number of specimens tested would also make it easier to distinguish genuine material differences from experimental variation. Such standardized reporting is particularly important because the ballistic response of STF-treated textiles can change substantially with testing conditions (Ribeiro et al., 2022; Lu et al., 2019).

REFERENCES

- [1] Brown E, Jaeger HM. Shear thickening in concentrated suspensions: phenomenology, mechanisms and relations to jamming. *Rep Prog Phys*. 2014 Apr;77(4):046602. doi: 10.1088/0034-4885/77/4/046602. PMID: 24695058.
- [2] Chamola, R., Das, S., Ahlawat, D.S., Mishra, Y.K., Goyat, M.S., 2024. Recent developments in shear thickening fluid-impregnated synthetic and natural fiber-reinforced composites for ballistic applications: a review. *J Mater Sci* 59, 747–793. <https://doi.org/10.1007/s10853-023-09201-z>
- [3] Chen, Z., Jing, Y., Wang, H., Zhang, X., Long, S., Yao, X., 2024. Fluid-structure interaction mechanism in shear-thickening fluid/foam composite for advanced protective structures. *Materials Today Communications* 41, 110662. <https://doi.org/10.1016/j.mtcomm.2024.110662>
- [4] Gürgen, S., Kuşhan, M.C., Li, W., 2017. Shear-thickening fluids in protective applications: A review. *Progress in Polymer Science* 75, 48–72. <https://doi.org/10.1016/j.progpolymsci.2017.07.003>
- [5] Khodadadi, A., Liaghat, G., Vahid, S., Sabet, A. R., & Hadavinia, H. (2019). Ballistic performance of Kevlar fabric impregnated with nanosilica/PEG shear thickening fluid. *Composites Part B: Engineering*, 162, 643–652. <https://doi.org/10.1016/j.compositesb.2018.12.121>
- [6] Lee B-W, Kim I-J, Kim C-G. The Influence of the Particle Size of Silica on the Ballistic Performance of Fabrics Impregnated with Silica Colloidal Suspension. *Journal of Composite Materials*. 2009;43(23):2679–2698. <https://doi.org/10.1177/0021998309345292>

- [7] Lee, Young & Wetzal, E. & Wagner, Norman. (2003). The Ballistic Impact Characteristics of Kevlar Woven Fabrics Impregnated with a Colloidal Shear Thickening Fluid. *Journal of Materials Science*. 38. 2825-2833. <https://doi.org/10.1023/A:1024424200221>
- [8] Long, S., Chen, H., Yao, X., Liu, T., 2025. Response of shear thickening fluids to high-velocity ballistic impact. *International Journal of Impact Engineering* 200, 105248. <https://doi.org/10.1016/j.ijimpeng.2025.105248>
- [9] Ribeiro, M.P., Da Silveira, P.H.P.M., De Oliveira Braga, F., Monteiro, S.N., 2022. Fabric Impregnation with Shear Thickening Fluid for Ballistic Armor Polymer Composites: An Updated Overview. *Polymers* 14, 4357. <https://doi.org/10.3390/polym14204357>
- [10] Wyart M, Cates ME. Discontinuous shear thickening without inertia in dense non-Brownian suspensions. *Phys Rev Lett*. 2014 Mar 7;112(9):098302. doi: 10.1103/PhysRevLett.112.098302. Epub 2014 Mar 6. PMID: 24655284.
- [11] Zhang, Y., Wei, J., Li, X., Miao, Z., Hou, J., Wang, P., Lv, E., Yao, Y., Zhang, K., 2025. Sintering, toughening mechanism, and amorphization of B₄C-based ceramic composites: A review. *Journal of the European Ceramic Society* 45, 117075. <https://doi.org/10.1016/j.jeurceramsoc.2024.117075>