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A NOVEL APPROACH FOR ARMOR APPLICATIONS OF SHEAR THICKENING FLUIDS IN AVIATION AND DEFENSE INDUSTRY

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Abstract: *At the beginning of 2000s, armor technology introduced to a new material: shear thickening fluid (STF). Due to the thickening behavior of this fluid under the stress, liquid state of the material turns into a solid-like state in a very limited time interval. This unique behavior of STF is intended to be used in armor systems. This paper offers an overview of STF properties and armor applications using the STF technology.*

Keywords: *Shear Thickening Fluids, Armors, Aviation, Defense Industry*

1. INTRODUCTION

Armor systems have a remarkable importance for the area of security and military. From past to present there have been different kinds of personal armor systems used to eliminate the attacking threats. Early applications used bulk layers of leathers covering around the body as the personal armor systems. By the emerging of advance weapons, metal armor systems came into prominence such as steel shields. Metal armors were safe but unfortunately heavy to act freely during the combats. For this reason, recent studies have been focused on ceramic composites and light ballistic fabrics such as aramid based fabrics.

At the beginning of 2000s, shear thickening fluids (STF) were thought to be used as armor materials then inevitable development in the defense industry started. Usage of these fluids merely or combined with the other armor systems not only provides protection also flexible motion for the users.

2. SHEAR THICKENING FLUIDS

Shear thickening fluids are an example of non-Newtonian fluids which have increasing viscosities since shear stress is applied. Even the shear stress reaches the upper levels, fluid shows solid-like behavior for a split second. After removing the stress from the medium, fluids turn to the initial liquid behavior [1-9]. STFs are seen as appropriate armor materials with their unique characteristics.

History of STFs in the investigation area is quite new and not more than 50 years. Improvement of the research techniques such as latest rheometers, scanning methods, rheo-optical devices and Stokesian dynamics, gave us a chance to understand the STF mechanism profoundly [10]. Because discontinuous characteristics may be seen at the critical shear rates, stress controlled rheometers are more convenient than conventional type rheometers.

Beside Stokesian dynamics simulation is used widely to simulate the behavior of many-body interactions in the suspension [11].

Plenty of non-Newtonian fluids can be found in the nature, but STFs are very rare. The most common example is wet sand at the beaches. Another easily accessible example is cornstarch in water suspension whose rheological behavior is given in Figure 1.

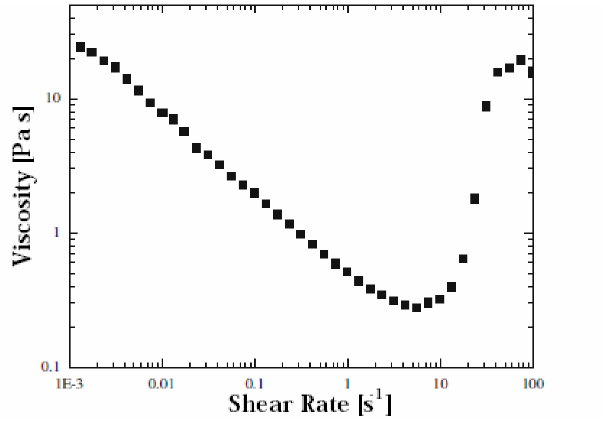


Figure 1. Rheological behavior of 55 wt% cornstarch in water suspension [9]

2.1 Mechanism of STFs. There are two main theories explaining the mechanism of STFs: order-disorder and hydroclustering.

Hoffman made the pioneering study about the micromechanical of shear thickening. This study became the basis of order-disorder theory. He proposed that below the critical shear rate, particles in the suspension are in a hexagonally packed order. After the critical shear rate, this packed particles disorder and particles aggregate. This transition from order to disorder causes a drastic increase in the viscosity [12].

Hydrocluster theory was first introduced by Bardy with Stokesian dynamics simulations [13]. This theory was supported by neutron scattering, rheological and rheo-optical tests as well as computer simulations [14-17]. Hydrocluster mechanism arises from particle interactions in the liquid suspension. Under the high level stress, particles have contacts each other. This effect yields an increase in the hydrodynamic forces. Then hydroclustering emerges which is defined as aggregation of the particles with increased viscosity and jammed behavior of the fluid [16, 17].

Behavior of the particles in the suspension is seen in Figure 2. In the shear thickening zone, dark particles indicate the hydroclusters in the suspension.

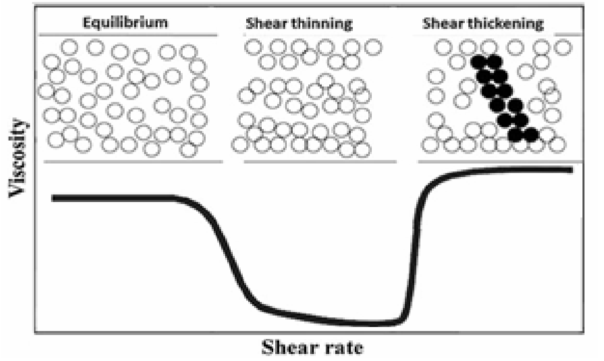


Figure 2. Particles in suspension [18]

2.2 Particle effects in suspensions. STFs are obtained by constituting suspensions with solid particles in appropriate liquids. These suspensions can be prepared in many different ways. Since the mechanism of STF depends on particles behavior, particles have strong influence in the suspension characteristics.

Particle effects can be defined in terms of particle volume fraction, particle shape, particle size, particle size distribution, and particle interactions [1, 18-21].

Particle volume fraction is defined as the fraction of total volume by particle volume and said to be the most important parameter in the thickening mechanism. A lower limit value is reported for the thickening behavior by Barnes *et al.* [20]. It is stated that above the volume fraction of 0.5, behavior of fluid changes drastically with the change in shear rate. Critical shear rate, which is defined as at which the shear thickening begins, decreases with the increase of particle volume fraction. Figure 3 shows the effect of the particle volume in the suspensions.

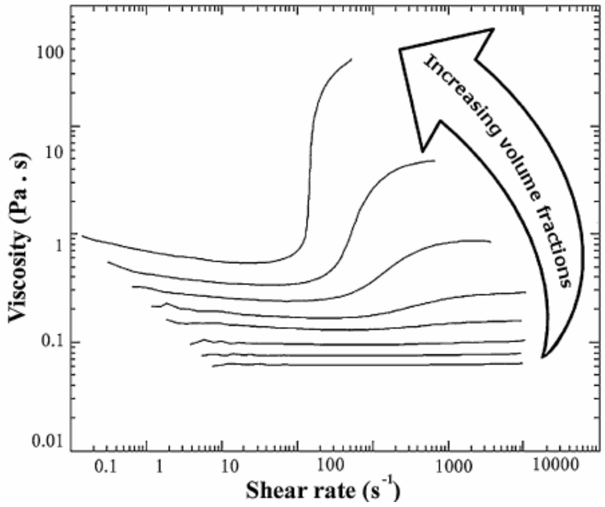


Figure 3. Effect of particle volume fraction [23]

Particle shape is another parameter having effect on the characteristics of the suspensions. Sharp edged particles in the suspension cause quick thickening as seen in Figure 4. Suspension with rod particles has the critical shear rate of 100s^{-1} whereas with sphere particles this rate is about 300s^{-1} [20].

Beazley [24] also states that particle rotation during flow may result in particle interlocking and jamming. With the high aspect ratio particles such interlockings will be seen more easily at lower particle volume fractions. Therefore, suspensions with high aspect ratio particles require lower critical volume fraction to achieve shear thickening.

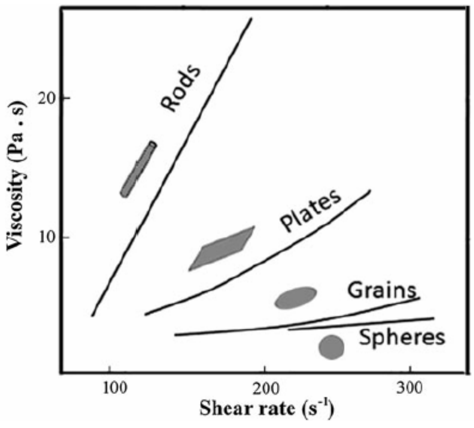


Figure 4. Effect of particle shapes in the suspension [20]

Particle size is another important parameter in STF behavior. It is known that as the particle size increases, critical shear rate decreases [20]. Figure 5 shows the relation between particle size and critical shear rate.

Particle size distribution affects the critical shear rate in the suspension. It is noted that critical shear rate increases when the particle size distribution becomes wider. Shear thickening can be achieved at lower shear rates by eliminating the small particles from the suspensions [20].

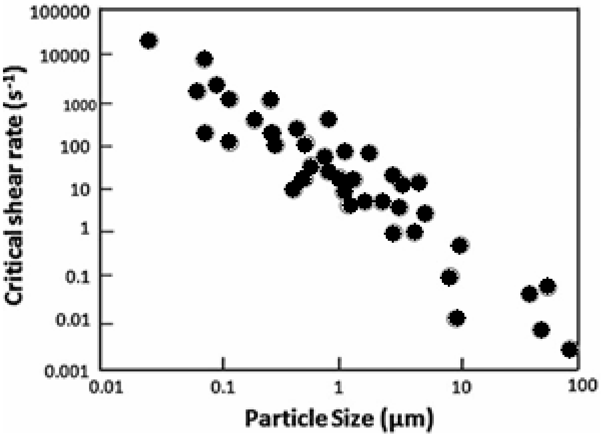


Figure 5. Effect of particle size in suspension [20]

Particle interactions have an influence on the shear thickening behavior. Particles in the suspensions may be neutral or repulsive to another by the effects of electrostatic, entropic, or steric interactions. It is stated that viscosities of deflocculated suspensions are lower at low shear rates. Shear thickening of these fluids occurs at high shear rates. On the other hand, viscosities of flocculated suspensions are higher at low shear rates. These fluids show shear thinning at high shear rates [1, 20]. Figure 6 shows the effect of chemically induced flocculation.

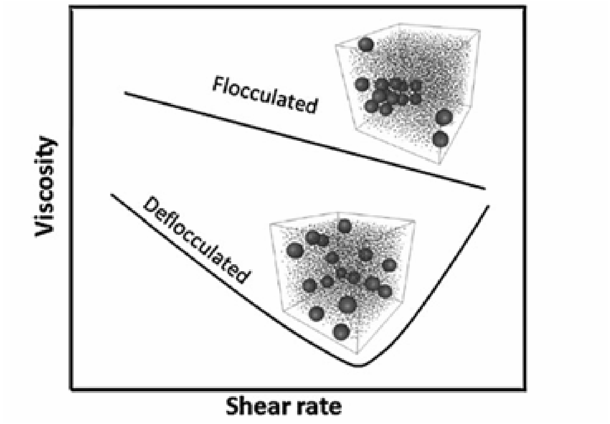


Figure 6. Effect of chemically induced flocculation [20]

Beside the parameters given above, additional parameters can be shown as examples. Hardness of the particles is one of these parameters. Shear thickening behavior increases with increase in hardness of the particles [21]. Another parameter is temperature which improves the shear thickening behavior by decreasing [25].

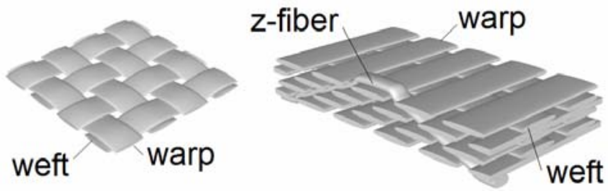
Some studies focus on the methods for improving the shear thickening behavior. For example, nano fillers are used to improve the shear thickening. In this method, nano fillers increase the dispersibility of nano particles which enhances the interaction between the particles and results in a better particle clustering. To achieve this, carbon nano tubes (CNTs) are applied into silica-poly ethylene glycol suspension. It is noted that CNT reinforcement improves the dispersibility of nano particles in the suspension [19].

3. ARMOR APPLICATIONS

Armor technology has been continuously improved like weapon technology. These two terms always keep up with each other. Ballistic protection has to be actual to overcome the attacking threats. Therefore, every kind of material has been considered as armor materials such as aluminum, steel, leather and silk. Principally, the method of protection uses a hard rigid material for resisting the penetration of missiles. But, after the debut of synthetic textiles, better ballistic armors have been developed [26].

3.1 Fabrics in protection. Ballistic fabrics are made of high strength fibers and chosen due to their high energy absorption capacity and proper tenacity/weight ratio. Furthermore, ballistic fabrics provide easy motion for users with their flexible structures [27-29].

Energy absorption and propagation capacity of fabric layers are related to the tensile modulus of fibers. Fibers having high tenacity and high elastic modulus are chosen for production of ballistic fabrics. In addition to this, construction of the fabrics has an intense effect on ballistic performance. In the construction of these fabrics, warp and weft yarns are woven by using different weaving types such as plain and basket types. Generally, warp and weft yarns are selected with identical strengths to achieve the same properties in all directions [30]. Then, woven layers are piled on each other to obtain laminated fabrics. Laminated fabrics are called 2D fabrics and the major problem is delamination. Latest studies focus on 3D fabrics in ballistic protection. 3D fabrics have yarns running in three directions therefore, delamination problem is decreased by the reinforcement of yarns along the third direction [31-41]. Figure 7 shows fabrics in 2D and 3D forms schematically.



(a) (b)

Figure 7. Fabrics in (a) 2D form (b) 3D form

3.2 Application of STFs in ballistic protection. Although STFs are worldwide known, application of these materials in ballistic protection is quite novel. First studies were started at the University of Delaware in mid 1990s. Considerable results were attained at the beginning of the 2000s. Composites of Kevlar® and STFs were introduced as armor systems in the publications. This technology was also supported by Army Research Laboratory. In 2004, a patent application [42] was filed with the cooperation of University of Delaware and Army Research Laboratory [1].

The most important gains in STF based armors are reduced weight and flexible motion. In the combat zones, conditions are already crucial. In additions to these difficulties, struggling with the equipment and the armor makes the soldiers daunted. Average combat loads for U.S Army soldiers in Afghanistan 2003 are given in Table 1.

Table 1. Average combat loads for U.S Army soldiers in Afghanistan, 2003[43]

	Average Fighting Load	
Duty Position	Weight (kg)	Percentage of Body Weight
Rifleman	28	36
Automatic rifleman	36	45
60mm mortar gunner	29	38

In 2001, U.S Army Chief of Staff expressed a goal that the combat load of the individual soldier was not to exceed 23kg [44].

Wagner *et al.* [45] studied characteristics of STF impregnated Kevlar®. It is noted that starting shear rate values of thickening behavior are between 10s^{-1} and 300s^{-1} whereas the shear rates estimated in the ballistic shootings are at 45x10^{3}s^{-1} based on the projectile velocity. Therefore, the STFs used in the study are ready to exhibit thickening behavior in the ballistic tests. In the conclusion of the study, it is stated that STF impregnated Kevlar® has the highest energy dissipation value with respect to the neat Kevlar® and ethylene glycol (EG) impregnated Kevlar®. EG impregnated Kevlar® has the worst protection level because EG is Newtonian fluid and serves as lubricant between the yarns and the projectile. Figure 8 shows the energy dissipation percentages of armor constructions by considering the armor weights.

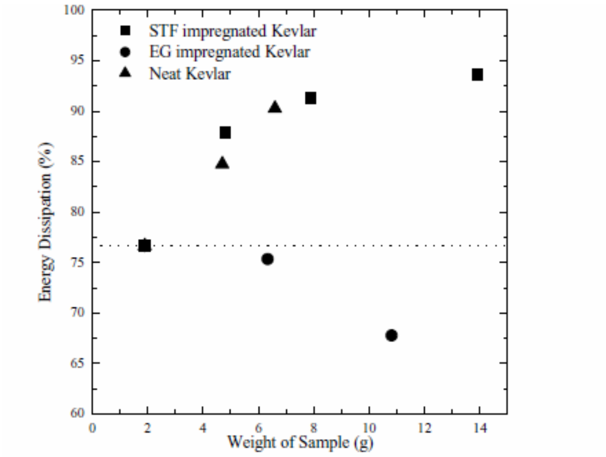


Figure 8. Energy dissipations of targets [45]

In another study using STF-Kevlar® composites, particle volume fraction of STF is investigated. As in the pure STF, thickening mechanism is more intense on fabrics with high volume fractions of particles. Furthermore, at low particle loadings, ballistic performance is less than neat Kevlar® while at high loadings is better than neat Kevlar® [23].

Tan *et al.* [50] studied single, double, quadruple and six ply Twaron® fabric systems with different percentages of STFs. Ballistic tests showed that the best protective system is double ply fabric impregnated by 40wt% STF. This system improves the ballistic limit by 65% compared to the neat double ply system.

In the studies, finite element method is preferred for modeling the STFs on fabrics. But, it is quite complicated to define the properties of STF in the model. To overcome this problem, Kim *et al.* [51] modeled the STF impregnated Kevlar® without modeling the liquid STF. Since STF increases the friction between the yarns, a friction function dependent to velocity was obtained by conducting yarn pull-out energy tests. In the conclusion, good agreements between simulation and ballistic tests were achieved in terms of residual velocities.

3.3 Application of STFs in stab protection. STF reinforced fabrics can also be considered as protective armors against stab attacks. In the literature, studies investigating this issue are available.

Protection of STF impregnated ballistic fabrics is determined by conducted some tests. These tests are generally performed in two ways: drop stab test and quasistatic test. It is proven that STFs reinforce the Kevlar® significantly for spike impacts while slight improvement is seen for knife impacts. Also in the quasistatic tests, for puncturing the same thick armors, STF-Kevlar® composites require two times more load by knife and five times more load by spike with respect to the neat Kevlar® armors [19, 46, 47].

Decker *et al.* [48] and Gong *et al.* [49] studied the stab resistance of the armors at the fiber level. Deformation of ballistic fabric fibers were investigated by SEM imaging. It is noted that STF restricts the fiber mobility which prevents the sharp tip of the spike from pushing aside fibers and penetrating between them (windowing effect). This effect is also seen in knife stabs but since cutting takes place in knife stabs, fiber mobility cannot be restricted effectively. This mechanism explains that protection of STF impregnated fabrics is higher in spike stabs than in knife stabs. Figure 9 shows the load-displacement curves for quasistatic loading of Kevlar® and STF-Kevlar® targets against both spike and knife impactors.

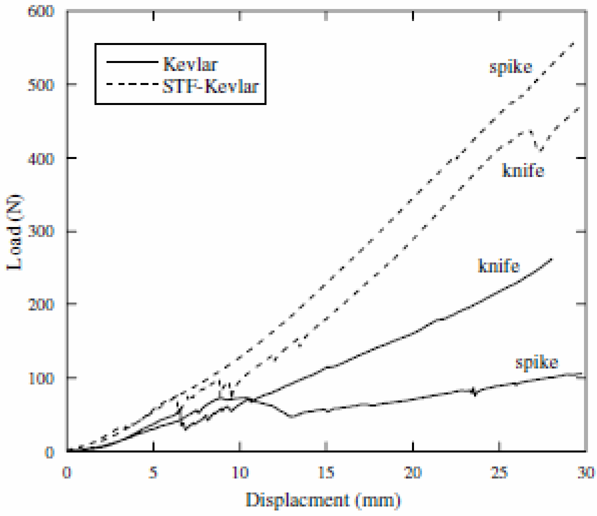


Figure 9. Load-displacement curves for quasistatic loading [47]

4. FUTURE DEVELOPMENT

STFs in armor systems are very new technology and open to developments. This technology provides two main improvements: reduced weight and flexible motion. Whenever reduction in weight comes into question, any relation with aerospace industry may take place. Thus, STFs can be applied to aerial vehicles such as helicopters beside the personal protection. Today it is just an idea however, in the near future it might be possible that this technology can protect the aerial vehicles.

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