Recent Advancements in Shear Thickening Fluid Applications-A Review

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ABSTRACT

This paper reviews in detail, the various developments in the experimental study of colloidal shear thickening fluid (STF) and its applications in enhancing the impact energy absorption of aramid fabrics and polymers, concentrating on application development work in the fields of ballistic protection, body armour, shock absorption and damping devices, over the last 3 years (2013-2016).

KEY WORDS: Shear Thickening Fluid, Body Armour, Aramid, Ballistics, Damping.

1. INTRODUCTION TO SHEAR THICKENING FLUIDS (STF)

Shear thickening fluids or Dilatant fluids are a type of Non Newtonian fluids that exhibit increase in their dynamic viscosity with increase in the rate of shear deformation or shear rates. Typically a shear thickening fluid consists of a colloidal dispersion of non-aggregating particles in a polar organic solvent. But this is not a necessary condition for shear thickening phenomenon. A general example is fumed Nano silica dispersed in poly ethylene glycol.

The favourable properties of the dispersed phase / particles have been listed out and likewise the importance of polarity, OH bonds and stability of the medium has been detailed in earlier studies by various scholars.

The use of dilatant fluids in various fields like body protection ware, shock absorption devices and sports protective equipment has become popular over the past few years. One such important application is the use of shear thickening fluid – aramid fabric composites to improve the ballistic and impact resistance of body armours like Kevlar bullet proof vests etc.

Though this field has been researched and reviewed many times before, the various important developments of the past 3 years have yet to be reviewed in detail, and that is the premise of this review paper.

Other earlier reviews related to this field include

- A review of the classifications on the types of non-Newtonian fluids in general .The review also includes the trends and developments of certain industrial applications of the same like Mechanical processing, Damping etc. (Peng, 2014)
- A review published by Ding (2013), and others studies the mechanism of Dilatant fluids as well as the factors affecting it. Further specific applications like smart textile materials etc. have also been studied upon.
- Another review studies in particular the various trends in studying the impact resistance of STF composites. (Hasanzadeh and Mottaghitalab, 2014)

In this review paper, the recent advancements on the study of the general properties as well as the applications of Shear thickening fluids over the last three years have been compiled, to understand the direction of future research.

Properties of Interest In Shear Thickening Fluids: The recent development in the properties of shear thickening fluid and its composites with special regards to the improvement in their stab (resistance to the force exerted by means of an edged blade) and ballistic resistance as well as its dampening behaviour have led to many innovative applications that have been detailed in this review.

Stab and puncture response: Some of the recent developments in the study regarding stab and puncture resistance/ behaviour of colloidal shear thickening fluids are as follows.

A study of the stab and puncture resistance of STFs of different composition impregnated in fabrics was conducted and it was concluded that the inter yarn friction was the most significant contributor to the puncture resistance while the particle hardness played the most important role in stab resistance of the fabric. Further mechanisms explaining the above phenomenon were discussed under the assumption that the enhancing effects of the particle and the medium on the fabric were different (Gong, 2013). Even a recent study was conducted to recognise the effect of concentration of polymer in STFs and to find the optimum mixture of Poly Ethylene Glycol (PEG) and Nano silica for maximum efficiency in protective clothing purposes (Hsieh, 2016).Hypodermic needle puncture tests were conducted to predict and understand the role of mobility of yarn and yarn friction in impact resistance. It was concluded that simple intercalation of yarn with STF improved the yarn friction and puncture resistance, while inter fabric layer friction played a more complex role both of which depended also upon other process parameters like needle size, fabric weave structure etc. (Cwalina, 2015).

The variations of the characteristics of Nano silica STF dispersion in aramid fabric including stab resistance, critical shear rate, etc. with silica mass concentration were studied. It was also seen that with increase in mass concentration, the initial viscosity also increases. It was concluded that STF impregnated fabric showed better stab resistance as compared to neat fabric (Fanglaet, 2013). Further it was seen that the increase in viscosity increased with concentration of particles and that both stab and ballistic resistance were significantly enhanced. It was also found that the viscosity modulus was greater than the elastic modulus of the STF- fabric and the values were used to explain the behaviour of the composite under various strain % (Yıldız, 2013).

The effect of STFs on the quasi static puncture resistance of p-aramid fabrics was studied. It was seen that decreasing particle size lead to increase in viscosity and critical shear rate. The puncture resistance of the fabric was greatly enhanced by the STF. It was also noted that decreasing particle size reduced the deformation and increased the maximum load of the fabric when subjected to puncture tests (Baharvandiet, 2014). The effect of silica weight fraction on quasi static puncture resistance was studied .The increase in silica concentration not only increased the critical and ultimate viscosity but also increased the energy absorption capability and the maximum bearable load significantly (Baharvandiet, 2015). It was noted that the quasi static puncture resistance increased 4.5 times for 35% conc. STF impregnation in Twaron (ASTM test-standard D6264) (Baharvandi, 2014) Also, under similar conditions, STF- Twaron composites required higher loads to achieve penetration as compared to regular Twaron fabric (Zielinska, 2014).

Further the effect of STF on the properties of ultra-high weight molecular polyethylene (UHWMPE) was investigated and a significant increase in the spike (resistance to spike penetration such as a nail penetration) and stab resistance was observed. Further the stab resistance was seen to be dependent on the mass fraction of the silica particles in the STF. It was also noticed that the flexibility of the UHWMPE was also greatly improved on impregnating with STF (Sun, 2013). Another detailed investigation of the dynamic stab resistance of UHMWPE impregnated with STF revealed that STF increased yarn mobility and transverse fabric response and hence increased the stab resistance. Further analysis showed that various poly ethylene glycol additives affected the stab resistance of the fabric and it was seen that increasing the chain length and concentration of the same increased the stab and spike resistance of the fabric (Li, 2016).

Ballistic impact response: The effect of particle strength and fluid density on the penetration and ballistic resistance of a STF was investigated and it was seen that the particle strength plays an important role in determining the response to impact (Petelet, 2013). Further a study conducted to investigate the effect of particle strength in ballistic response of various Newtonian and non-Newtonian solid- liquid dispersions showed that large particle strength (like that in case of silica etc.) in shear thickening fluids alone show significant deviation from expected behaviour. The effect of particle strength diminishes under high and very high velocity impacts (Petel, 2015)

Impact based applications of STF aramid Fabric composites were studied under various parameters like cushioning, shock absorption, energy dissipation, comfort etc. Special regard was given to the study of the low velocity impact response. Further the possible applications of STFs based on their low velocity impact response were also predicted (Xue, 2015). The effect of particle size on the ballistic response of aramid fabrics impregnated with STFs was studied and it was concluded that reducing the particle size increased the ballistic performance. Particle scale investigation revealed that smaller particle sizes increased the adhesion property of the particle with the yarn, leading to better coupling / bridging in the inter yarn level (Wang, 2015).

The effect of STFs impregnated in Kevlar when subjected to high velocity ballistic impacts was studied and the differences in the post impact rear formation of the Kevlar composite when compared to that of neat Kevlar was also investigated (Park, 2013).

A study was conducted to realise the impact properties of STF- UHMWPE composites made of 2 dimensional UHMWPE and Nano silica- PEG STF. The high speed impact analysis of STF- UHMWPE with unidirectional fabric target were tested against regular 2d fabric with UD target and it revealed that STF- UHMWPE showed 10-13% decrease in damage depth and up to 38% reduction in damage diameter (Wang, 2015).

Load / shock response – energy absorption characteristic: A study of the energy absorption properties of mono dispersed Silica based STF was performed using low frequency oscillatory tests and by measuring the energy dissipation in each cycle. Influence of various parameters like particle concentration, viscosity etc. were also studied. It was concluded that STF based dampers showed advantage in high strain applications (Soutrenon M and Michaud, 2014). Further the behaviour of STF has been studied experimentally using Kolsky method and the hysteresis of the impact load unload cycle was observed and the energy dissipation was observed (Bragovet, 2014).

It was further detailed that changing the oligomer chemistry and the molecular weight of the dispersed particles and the medium helped customize the impact characteristics/ energy absorption properties of STFs and Magneto rheological fluids as per requirement (Leonowicz, 2014). Efforts to optimize the energy dissipation of STFs lead to a study on optimizing the ethanol content in traditional silica- PEG STF. Damping properties of various samples of STF were tested and it was concluded that the STF showed maximum energy absorption when the ethanol to Silica ratio was 3:1 (Kordani and Vanini, 2014).

The propagation of a stress pulse in regular PEG and Nano silica – PEG was studied and it was noted that reversible energy dissipation was present in the STF and the pulse attenuation was much greater when compared to the regular PEG (Jiang, 2013). A study of the response of laser induced shock in a STF was conducted and it was observed using photonic Doppler velocimetry that the wave and particle velocity decreased significantly during shock wave transmission. This phenomenon was attributed to the jamming of particles under stress and other such properties of STFs. Further an equation of state was derived for the STF. It was also noted that the energy dissipation steeply increased with the increase in the layer thickness of the STF (Wu, 2015). Further experimental study showed that the shock wave attenuation also depended upon the temperature, shock pressure and stress states of the STF. It was also noted that a critical stress pressure was required to induce shear jamming of particle matrix in uniaxial strain states (Wu, 2015).

A study was conducted to determine the properties of STF impregnated aramid fabrics under shear strain. Various tests like picture frame, uniaxial tensile test etc. were conducted. It was concluded that the STF only enhanced the existing inherent polymeric property of the yarn matrix like inter yarn friction etc. and was only partly responsible for the energy dissipation characteristics (Na, 2016). The high strain response of shear thickening fluid impregnated aramid fabric was investigated using a picture frame pull out test under various speeds. The results were analysed and an energy model was proposed to predict the same (Ahn, 2014).

The compressive behaviour of warp knitted spacer fabrics (WKSFs) impregnated with STFs was investigated and it was noted that the fabric showed strain rate effects under compression. It was also concluded that STF impregnated WKSF showed higher energy absorption and a decrease in peak load compared to regular WKSFs (Lu, 2013). Similar results were observed under finite element analysis of the microstructure of WKSF impregnated with STFs. It was shown that buckling of fibre tows and shear thickening played a combined role in energy absorption characteristics (Lu, 2015)

Properties of STF composites based on non aramid substrates: Apart from aramid fabrics like Kevlar and Twaron, there have been attempts to induce STFs into other types of substrates in order to improve their impact response for various purposes.

A recent study of the effects of STF – with Nano silica and Nano clay on glass fibres was investigated and it was found that the fibre exhibited enhanced penetration resistance with respect to neat glass fibres. It was also found that increase in weight fraction of Nano silica or Nano clay increased the displacement to yield point of the fibre (Balali, 2016).

High speed projectile penetration tests were conducted on symmetrical and asymmetrical sandwich plates filled with various concentrations of STF. The effects of particle volume fraction, thickness of the sheet, velocity of impact were all studied (Tan, 2016). Similarly experimental investigation of hyper velocity impact response of open cell sandwich plates made of iron foam core infused with STF was carried out and various features such as plane deformation, core damage and sheet penetration with STF and without STF were recorded (Warren, 2015).

The effect of hybrid composites made of 5086-H32 aluminium alloy, epoxy resin and Kevlar fibres and shear thickening fluids were studied under different configurations and properties such as energy dissipation, fabric deformation, penetration and the effect of thickness of the laminates were noted using a SEM microscope (Haro, 2016).

A novel , ecofriendly type of substrate made of micro agglomerated corck sheets with laser engraved micro channels was infused with STF .The effect of the STF on the cork sheets were investigated by performing low velocity impact tests. It was seen that the cork sheets showed an improvement in the peak force when infused with STF. A numerical analysis showed that the size of the micro channel and the inlet velocity played a role in the properties of the composite (Galindo-Rosales, 2015)

A smart ligament whose response to extension depends on the rate of extension was synthesised and studied. This material is made of elastomeric polymers and STFs. The rheological behaviour was compared to STF fabric composites and its applications were discussed (Nenno, 2014).

A stretchable poly urethane sponge like polymer composite was created using a novel dip and dry method. It was seen that this substrate showed excellent and tuneable shear thickening effect which was attributed to the B-O cross bonds in the sponge. This material showed damping up to 2 orders of magnitude and showed very little fatigue under continuous load – unload cycles. This material also possesses good creep resistance and adhesion properties making it suitable for a variety of applications (Wang, 2016).

Effect of Process Parameters on STF/ STF- Aramid Composites: In the past three years, various studies have been conducted to identify the optimum conditions for the use of shear thickening fluids. The effect of variation of process parameters such as temperature , padding pressure etc. affect the properties of the STF- Fabric composite and thus affects the potential applications of the same.

Effect of temperature: The effect of temperature on shear thickening fluids was studied and it was determined that the critical shear rate increased under high temperatures while the shear thickening ratio decreased under the same. Further these results were tested under various temperatures and a viscosity function was modelled to predict the viscosity of the STF under given temperature (Tian, 2013, 2015).

Another study of the temperature dependence of the STFs was conducted by varying the surface chemistry, composition and the particle dispersion factor over a varied temperature range. This study also returned the same result while also showing that the critical shear rates were inversely dependant on the viscosity of the fluid (Warren, 2015). Further research has revealed a certain gelation effect of Nano silica under elevated temperatures. This was found to occur when the concentration of the silica particles exceeded a certain critical value. Also the reason for gelation was found to be related to the changes in the hydrogen bonds as well as changes in the solvation layer at the surface of SiO2 particles (Liu, 2015).

Effect of pH: The effect of pH on the rheology of an STF - polystyrene ethyl acrylate was investigated and it was seen that pH can significantly affect the critical shear rate. It was seen that varying the pH near the solutions isoelectric point (the pH for at which a molecule of the statistical mean has no net electric charge) decreased the critical shear rate. This phenomenon was further explained using hydrodynamic cluster formation (Chen, 2014).

Effect of weave pattern: An investigation of the effect of weave pattern, and fabric set on the yarn pull out force showed that plain woven UHMWPE showed maximum yarn pull out force compared to other patterns under same sett. It also revealed that STF impregnation dramatically improved the yarn pull out force and hence drastically reduced the chances of yarn failure (Majumdar and Laha, 2015). Further, the effect of weave structure and yarn thickness was investigated using 5 different weave patterns of Technora yarns. It was noted that plain weave showed maximum energy absorption characteristics when not treated with STF. It was noted that STF improved the impact response of all weave types by increasing their yarn densities. Also it was noted that a plain weave structure with 30 × 30 thread density is the optimum material for soft body armour (Laha and Majumdar, 2016). An investigation into the effect of padding pressure on the impact energy absorption of STF- Kevlar composite showed that higher padding pressure (squeezing pressure) lead to lower add on % but increased the impact resistance. This characteristic was attributed to the increased uniformity of the distribution of silica particles (Majumdar, 2014).

Effect of chemical surface modification: The effect of chemical surface modification of STFs on their ballistic and stab response was tested using water solution of silicic and acrylic acids. It was found that even low concentrations of silicic acid solution had better stab resistance property than high concentrations of acrylic acid solution. This difference was rendered negligible under high velocity ballistic impacts (Grineviciuteet, 2014). Also, the effect of surface hydrophobicity and add on percentage of silica particles in various carrier fluids like ethylene glycol, butylene glycol etc. were tested and it was found that better add on resulted in better stab resistance of ultra-high molecular weight polymer (UHMWPE) fabrics. Further the morphology and cutting edge of UHMWPE were also analysed (Guet, 2014).

Effect of Additives on the Properties of STF: The dilatant properties of colloidal shear thickening fluids can be significantly altered by adding certain additives that change the inter particle behaviour or the particle medium interactions.

Effect of Coupling agents and coating on Nano Silica particles: The use of silica particles functionalized by organo Silane was studied and the results confirmed that silated silica particles showed better STF properties than STF in PEG solvent. This property was attributed to the increased number of bonds between Kevlar fabric and silica. Further methods to enhance the bonds were also studied (Lambert, 2008).The penetration and ballistic resistance of aramid fabrics impregnated with Nano silica was investigated when silane coupling agents were added to modify the surface chemistry of silica particles. Samples of fabric with and without the modified silica were subjected to ballistic impact and the results were analysed. It was found that the modified silica particles lead to increased ballistic resistance (Obradovic, 2014). Similarly, Nano silica particles coated with poly dopamine shells were suspended in PEG and their rheological properties were studied. It was found that the shear thickening effect of this STF was much better than regular silica- PEG STF. Further this new STF showed maximum viscosity of 194 Pa. A single step method was proposed to create these Poly Dopamine (PDA) shells of tuneable thickness and structural dependence of the STF on the particle was investigated (Liu, 2016).

Effect of carbon nano tubes: Nano fillers affect the property of STFs. A study of the effect of carbon Nano tubes and graphene Nano plates on the rheological behaviour of STFs showed that the shear thickening effect was clearly enhanced by them and it further revealed that the aggregation of the dispersed particles increased the shear thickening. This effect was attributed to the formation of Nano material clusters and a suitable model was proposed to explain the same (Sha, 2013).

Effect of graphene oxide: A study of the use of Graphene oxide (GO) as an additive to regular silica- PEG STF, showed that minute quantities of GO lead to enhanced viscosities, better storage modulus and also reduced the critical shear rate. Hence the use of GO was proposed to tune the properties of STFs for various applications (Huang, 2015).

Effect of ceramic additives: The effect of ceramic additives like silicon carbide and boron carbide was assessed by varying the process parameters and studying the properties using a rheometer. The results showed a general increase in the STF ratio, thickening period and viscosity of the STF on addition of the fillers though the exact responses depended upon the process parameters themselves (Gurgen, 2016). Further, the effect of silicon carbide additives in the properties of Fumed silica based STF was investigated by varying the amount of the additive and studying the properties of the STF under varying temperatures using a rheometer. The results showed that the effect of the additive significantly depended upon the process parameters like concentration, size of particle, temperature etc. (Gurgen, 2016)

Effect of metal powders: The effect of Nano fillers in the characteristic ballistic properties of hybrid lamina made of epoxy, Kevlar and H32 aluminium sheets was studied. The energy dissipation of neat Hybrid to that of Hybrid mixed with PEG 400 containing various Nano fillers like gamma aluminium, silicon carbide, aluminium powders etc. was compared under projectile impacts. The results indicated that aluminium powder showed maximum increase in energy dissipation followed by silicon carbide powder. The effects of these fillers was attributed to the increase in the inter yarn bonding of the hybrid and coating abilities of the filler (Haro, 2016).

Effect of abrasives: An investigation of the effect of abrasives on the shear thickening effect of STFs for the use of STF polishing was performed and it was determined that the effect of the abrasive additive depends on the type of abrasive. Further it was seen that the number of abrasive particles affected the STF and not the weight ratio of the additive (Lyu, 2016).

Effect of surfactants: The effects of adding surfactants to STFs were studied using cationic, anionic, zwitter ionic and non-ionic surfactants. It was found that all types of surfactants increased the shear thickening behaviour by affecting the surface and inter particle interactions. Further the effects of various surfactants were studied in detail and a plausible explanation for the said phenomenon was also discussed (Ye, 2013).

Alternative Applications of STF Composites: The energy absorption characteristics of shear thickening fluids have found many interesting applications. Apart from its use as liquid body armour, their applications in other fields have also been studied in the recent years.

Application in Thermal Micrometeoroid Garment (TMG): Due to its energy absorption and penetration resistant property, a recent study suggests the use of STF- Kevlar composites as a replacement to regular neoprene coated nylon covering in the thermal micrometeoroid garment (TMG) of extra vehicular activity suits (EVA suits).The increasing threat of micrometeoroids and orbital debris (MMOD) in the low earth orbit is due to their very high impact velocities and their penetration capabilities into the astronauts EVA suits. Hypodermic needle tests simulating the puncture and cut threat of MMOD revealed that replacing the standard nylon absorbers with STF Kevlar composites lead to significant increase in the peak puncture force and energy absorption levels of the suit without compromising on weight and flexibility (Cwalina, 2016). Hyper velocity impact testing of these TMG layers also revealed that STF – Kevlar absorbers were more efficient than their nylon counterparts (Cwalina, 2015)

Application in Trauma pads: The application of non-Newtonian fluids in the field of blunt trauma protection has been investigated. Trauma pads made of different types of non-Newtonian fluids like silica in PEG; Methyl-phenyl-borosiloxane polymer compositions etc. were placed in between ultra-high molecular weight poly ethene fibre layers and were subjected to ballistic tests. Further the use of foam based STF composites as trauma pads was also investigated. The results of these tests were used to identify the potential use of STFs in blunt trauma impact resistance applications (Pacek, 2016).

Application in Battery electrolytes: The use of shear thickening effect in electrolytes of batteries was studied and it was found that conducting STFs proved to be a potential replacement for commercial electrolytes in lithium ion batteries. Further detailed study was conducted on the efficiency of the electrolytes when silica particles were added and the impact resistance of these electrolytes on crushing of batteries was also tested (Ding, 2013).

Application as adhesive: The use of STFs as an adhesive was proposed and fracture analysis of the same was conducted to analyse the mode 1 fracture energy of STF using a double cantilever beam with STF as adhesive layer. It was found that the load rate played an important role in the ST effects. Further it was concluded that during shear thickening (and constant thickness of fluid layer), the fluid behaved as a solid, and classical fracture mechanics could be used to identify its crack/ fracture resistance (Tabassum, 2015).

Application in shock mitigation: The use of STFs in shock wave mitigation was studied by impregnating Twaron fabric with conventional silica- PEG STF and subjecting it to shock tube tests. The results showed a decrease in both normalized average peak pressure as well as the rate of rise in pressure. It was also concluded that the apparent density of the material correlated with the above properties (Haris, 2015).

A new type of Nano composite based on STFs was designed and its peak force and energy absorption efficiency was studied. It was seen that for low energy impacts, the composite behaved like regular impact foam, but for impact energy over 15 J the composite showed better energy absorption capabilities (Fowler, 2015).

A new type of STF based damper was created and its properties were studied. It was noticed that this damper showed maximum output force several orders higher than conventional STF based damper. The properties of the design were studied and a model was proposed to explain the non-linear damping performance of the STF based damper (Zhou, 2016).

Application in Anti-Vibration mount: An anti-vibrational mount was developed that worked in real time and used the damping properties of Silica – ethanol STF. Its various properties were tested and it was concluded that the transmission of vibration at resonance frequency and high acceleration was reduced significantly. The device proved to be more efficient than its traditional counterparts (Galindo-Rosales, 2016).

The various properties of a sandwich beam with an STF core was studied by producing forced vibrations. The effects of various parameters like skin thickness, excitation frequency/ amplitude/location etc. were studied and it was concluded that the STF core reduced the amount of vibration in the sandwich beam (Wei, 2016).

Magneto rheological Shear thickening fluid (MRSTF) is a type of fluid formed when magneto rheological materials and shear thickening fluids are combined to produce both MR as well as dilatant effects in the same material. A study of the properties of these fluids proposes the use of MRSTFs as a semi active energy absorber in linear dampers. A prototype damper using MRSTF as the absorber was created and analysed. It was concluded that the MRSTF damper showed variable damping coefficients that depended on shear as well as changing magnetic flux (Tian, 2013). Another study was conducted to analyse the effect of weight fraction of carbonyl iron particles on the properties of the MRSTF based linear damper. It was concluded that low weight fractions (20%) lead to significant display of both MR and ST effects allowing the damper to work in different dynamic load velocities. On the other hand high weight fractions (80%) lead to the properties of the magneto rheological material dominating over the shear thickening effect (Yang, 2015).

Possible Scope for Further Research: Though the mechanism for shear thickening of colloidal STFs has been studied extensively, there is no clear cut procedure to estimate whether a combination of a fluid and an additive will lead to Shear thickening or not. Further there is scope for molecular dynamic research to explain the properties observed experimentally.

There is a need for optimization of the process parameters in the STF – Fabric composites with regard to stab, ballistic and vibrational energy dissipation applications (on an application to application basis) as properties such as add on % and particle sizes affect the same either directly or inversely (depending on which resistance is in consideration).

Several Organic fluids and Nano additive composites are being used in the present. Ex. Additives are being used in fuels like petrol, diesel and biodiesel, for performance enhancement. The possibility of unprecedented shear thickening in such colloidal dispersions like fuels etc. has to be studied to reduce or optimize the effects of the same. There is scope for more real time applications of colloidal shear thickening fluids.

2. CONCLUSIONS

This article reviews the properties of interest of Shear thickening fluids and the various applications that are being developed using STF. The gap in literature and possible future directions of research are highlighted.

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