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Investigation of high velocity impact on shear thickened fluid woven composite

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Abstract: The protective vest is an important accessory to absorb impact energy and stop bullets from penetrating the body. Many modern vests are made by polymer matrix composites reinforced with kevlar, glass, and carbon fibers. The presence of water increases the friction between the bullets and the fibers and, as a result, increased the yield of the fabric. The shear thickening fluid (STF) is composed of silica particles dissolved in the liquid phase (e.g., polyethylene glycol). Silica particles are about a few nanometers in diameter. In equilibrium, the liquid phase is filled with colloidal hard particles. At high shear rates, hydrodynamic forces overcome intrusive repulsive forces. So after collision, the colloid particles of the material harden. In this study, experimental and numerical studies of impact on two and four layers of KFLF dipped with STF liquid with different percentages of nanosilica percent were investigated. Numerical modeling was performed with AutoDyn software. By comparing numerical simulation and experimental, good agreement between results of the ballistic limit is obtained.

Keywords: Kavlar yarn, shear thickening fluid, impact, ballistic limit.

1. Introduction

One of the first equipment that mankind aware for its usage was armor. Ancient humans made a thick skin of some animals to cover themselves to less harm from wild animals. Gradually, the use of various metal armors was expanded by familiarizing humans with metal forming techniques. Until the 14th century, the armor was so tight that the weapons of that time were almost unprofessional. It changed completely in the fifteenth century, with the advent of warm weapons. The firearms were so fast that they provided the energy needed to pull the armor. In addition, the thickness of the armor enlarged but this change caused the weight to be lifted and the use of the armor was limited. Years ago, armor had been lagging behind weapons until scientists in the twentieth century, especially in the sixties, relied on the advancement of metallurgical knowledge and the development of a new and protective vest.

Instead of using heavy metal parts, new armor is made of high-strength fibers in a high-density network. Their mechanism of action is that by relying on their grid structure, they scatter and absorb the energy of the bullet widely, but they should not be displaced into the body. As it can cause severe damage to the internal components of the body. In general, vests are divided into soft and hard types, which usually wear soft underwear and are less resistant to hard wear. The most important fiber used in Kevlar protective jackets. It is five times stronger than its own weight steel. Due to the cost of production, Kevlar production is still the best option for protective vests. Another thing that we all are familiar with is the spider web, the synthetic example of which is called bio steel, and its strength is twenty times as high as steel, but its cost is very expensive.

In contrast to the modern armor, special bullets to Teflon forehead (a material with a relative friction coefficient of almost zero) are provided, which, after colliding with the vest, drives the fibers to the sides and opens a path through the fibers to keep moving. Bullets are also produced with very hard metal carbide tungsten carbide or uranium 238, which concentrates the bullet energy at a point and fissures the armor. In contrast, for more resistance, vests cover them with special ceramic ribs such as aluminum oxide or titanium compounds. These plates (or polkaxes) can also withstand the bullets above the vests. In any case, each armor is resistant to a certain speed and caliber, and inefficient against high caliber. For example, most vests are even vulnerable to heavy-duty sniper rifles (12.7mm Sniper), such as those made by the Defense Department's defense industry. However, using its potential in the nanoscale, it is possible to produce very powerful armor so that it resists any caliber at a fast pace.

Koolar was first introduced by Dupont in 1970, and is the first high-tensile fiber and high-modulus fiber used in advanced composites. Because clay fibers have a lot of ballistic applications, so much research has been done in this area. In 1992, Brisco and Mutmi performed a blow test on a layer of Kevlar fibers [1]. The tests showed that the friction between the fibers is higher, the cloth will perform better. Bogenor also concluded that the presence of water increased the friction between the bullets and the fibers, and thus increased the yield of the fabric [2].

The factors influencing the ballistic performance of the fabric were material properties, geometry, projectile, projectile velocity, number of layers, boundary conditions, and friction [3]. Dian et al. Investigated the effects of friction on the ballistic performance of the cloth fabric and indicated that friction has a dramatic effect on the speed of the pickup and also delayed the breakdown of the fibers, thereby improving the fabric's ballistic performance [4]. Dian noted that improved fabric performance with the presence of shear thickening fluid is partly due to increased friction [5]. The behavior of the yarn was studied from five types of cloth-woven fabrics, and the results indicated that the pulling force had a direct relation to the fabric performance under the impact, and the cloth with a higher pull-up fiber had better performance in the tests Has a shot [6]. By studying on fabrics in which the fluid containing iron particles was impregnated, it was found to exhibit greater resistance to the impact when placed in a magnetic field [7]. Gadao tested the resistance to shaving aramid fabrics with a ceramic coating sprayed on the fiber. This coating is 50 to 100 microns thick and has a particle size of 22-10 µm [8]. It has been reported in studies that the thickening effect of the cutting is observed in a wide range of suspensions, including water-clay [9], water-calcium carbonate [10] and resin-titanium dioxide [11].

The presence of thickening fluid in the fabric is effective and increases the impact resistance. For the same resistance, the impregnated and non-impregnated fabric is impacted against the number of layers in the impregnated cloth less than the number of layers in non-impregnated cloth and more effective in impregnating fabrics against impact [12]. Dam and his colleagues examined the ballistic performance of a woven cloth dyed to a colloidal suspension of silica particles in water, with different concentrations of silica particles in water, and concluded that the ballistic resistance was related to increased friction between the bullets and the fabric and the friction Fibers are together [13]. Wagner and Lee investigated several positions of shear concentrated fibers and fibers relative to each other, and concluded that STF saturation with Kevlar was necessary to achieve an increase in fabric ballistic properties [14, 15]. Eric Duettel The ballistic and rheological experiments were carried out to obtain the effects of fluid viscosity, particle size and shape on the behavior of the coil-shaped composite impregnated with a shear thickening fluid, which indicates that increasing STF increases energy absorption by the clavicle fabric. This improvement in the properties of energy absorption of fabric with STF fluid can be due to increased friction between layers due to increased surface coating of nanoparticles on fibers and strands. Also, by increasing the volume percentage, energy absorption increases [16-18]. Jin Kang and colleagues investigated the effect of the STF fluid on clavicle fabric, and showed that the frictional resistance between the pickup and the impregnated cloth increases with the number of layers, while the non-impregnated fabric is not [19]. Also, Yuan Li and Hassan's rheology of non-Newtonian fluids and their viscosity increased with shear stress [20-21].

2. Material and required equipment:

The shear thickening fluid (STF) generally involves the propagation of colloidal solids in a fluid with a low Newtonian viscosity. Most studies in this regard have been carried out on the colloidal dispersion of silica particles due to their non-massive properties. In this research, a shear thickening fluid is obtained from the addition of silica nanoparticles in polyethylene glycol. Regarding the use of rheological fluid, STF is used from Kevlar fiber. The STF fluid also has the dilatant which having an unusual non-Newtonian behavior to a shear force. Figure 1 shows the dilatant behavior. Before impact, the liquid dilatant particles are in equilibrium and, after impact, are massed and together form a solid structure.

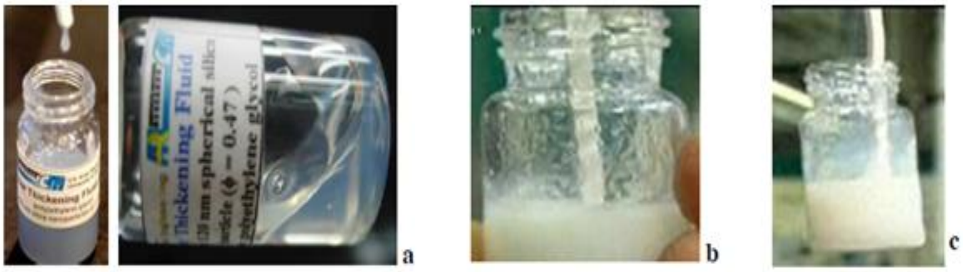

Figure 1. The dilatant behavior: a) shake in a fluid container without movement, b) bits off the plastic rod, c) with sudden force

Polyethylene glycol and silica, ethanol and kevlar fabrics, as well as homogenizers and furnaces are used to prepare the sample.

3. Specifications of Kevlar Layers

Kevlar fabrics are shown in figure 2 by dimensions of 7 × 7 cm. The fabric specifications are given in table 1.

Table 1: Property of Kevlar Fiber

texture type	Simple
Weight per unit area	220 gr/ m^2
Thickness	0.4 mm

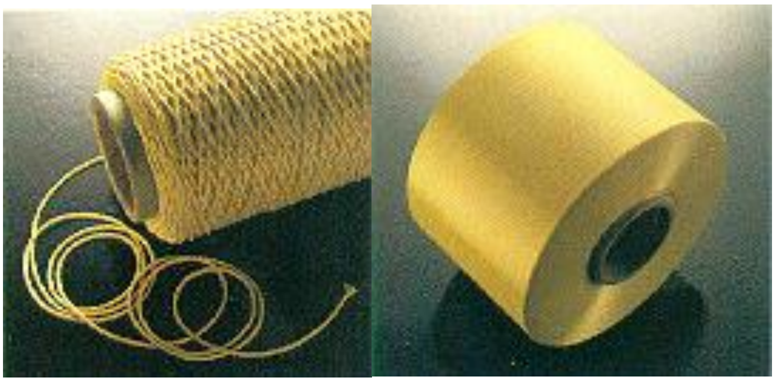

Figure 2 - Kevlar fibers

4. Scanning electron microscope

Scanning electron microscope (SEM) is the most commonly used imaging equipment. The advantages of this method, such as spatial separation, various imaging features, high capacity control, and user communication, make SEM before electron beam widths. The main task of scanning electron microscopy is the principles of drawing which is similar to the Fox machine. In other words, the electron-detector, as shown in figure 3, examines the sample surface in a two-dimensional material. Specific signals from the sample are used to change the intensity of the CRT electron beam, which is responsible for plotting the image in the CRT.

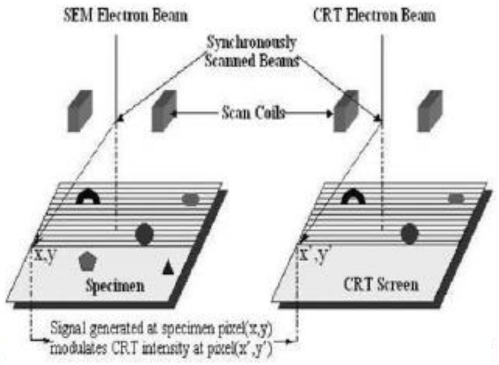

Figure 3. Schematic image of the SEM device

5. Specifications of the projectile used

The projectile is a spherical cylinder with a diameter and mass of 8.74 mm and 18.11 g, respectively. The diameter of the projectile is based on the internal diameter of gas rifle. The bullet shell is made of 4330 alloy steel and has a hardness of 40 Rockwells. To calculate before the collision, a device called a chronograph is used. Chronograph is a device that has two laser sensors that can be measured by passing a projectile. High-speed camera and chronograph are used to calculate the output speed of samples.

To determine impact velocity, the use of gas rifles is justified. The ultimate speed of the projectile coming out of the end of the gas gun tube is a function of the gun pipe, the pressure of the tank pipe, the coefficient of expansion of the gas used and the mass of the projectile. The ballistic experiments were carried out by a gun machine including parts of the feeding tank, the secondary reservoir, the solenoid valve, the actuator key, the connection flange and the pipe and fixture, the foils, the ballistic paste and the protective box of the device.

Preparing the gas gauge calibration curve is the first step in the ballistic test. It is necessary to obtain the desired curve for each specific bullet. For this purpose, at a constant pressure and different intervals up to the opening of the pipe, a number of free-firers are performed; and then the output velocity of the bullet from the tube is measured by the optical speedometer. Finally, the velocity curve is plotted in different spacing. Initial and residual velocities of projectile for two dried kevlar are shown in table 2.

Table 2. Initial and residual velocity of projectile for two dried kevlar layers

Initial velocity of projectile (m/s)	Residual velocity (m/s)
34	0
40	30
45	38
55	44

The ballistic limit or limit velocity is the velocity required for a particular projectile to reliably (at least 50% of the time) penetrate a particular piece of material. In other words, a given projectile will generally not pierce a given target when the projectile velocity is lower than the ballistic limit. In the tests, the ballistic limit and absorbed energy of specimens are obtained as a criterion of the ballistic performance of the fabric. To calculate the minimum energy needed to pierce the fabric, the energy of the bullet before impact should be deducted from the amount of impact energy after collision; therefore, the $1/2\ (M)(V0)^2$ bullet energy before the collision, V0, the firing speed, $1/2\ (M)(V)^2$ Bullet energy after collision and V Output speed of the projectile from the fabric and $1/2\ (M)\ (V0)^2 = 1/2\ (M)\ [(V0\ )^2-(V)^2]$is minimum energy required to pierce the sample. For each sample, a ballistic test was performed until the speed limit was reached. For firing a projectile at speeds above the speed limit, the projectile will have an outlet speed. In Table 3, the results of the test, including the ballistic speed limit and the minimum energy required to sample the hole, are presented.

Table 3. Ballistic limit of samples

	Experimental speed limit (m/s)
2dry layers	33.6
4dry layers	42.5
2 layers with 15% fluid	39.7
4 layers with fluid	62.4

6. Numerical modeling

The results of numerical simulation to find the ballistic velocity of different samples (two- and four-layer fabrics with STF percentages used in experimental tests) in two and four layers is shown in figures 5- 8. As can be seen, there is a good agreement between the results of the simulation and the empirical results.

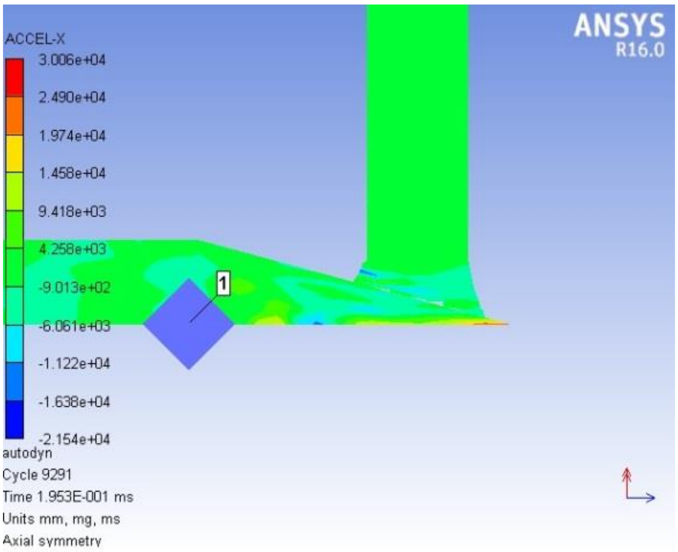

Figure 4 -Location of Gauge1 that makes the following graphs.

As you can see in Figure 4, the measure used to obtain the desired outputs is well. This measure is not at the tip of the projectile because it is subject to the greatest change of form. Consequently, in the nearest location, we placed the tip of the projectile, which has the smallest form of change. It goes without saying that the placement of the gauge even at the end of the projectile does not change the resulting charts.

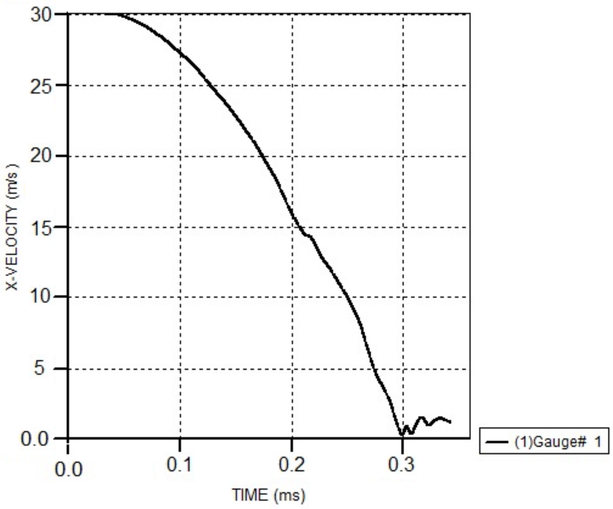

Fig. 5- The ballistic limited velocity graph of the bullet after collision for dual-layer droplet

As shown in Fig. 5, velocity of a dry-buoyant sample is obtained 34 m/s, which can be expressed in terms of the near-instantaneous speed to the empirical result. There is almost acceptable reliability for this simulation. Meanwhile, contact time of 0.003 second can be a significant time for these thin films.

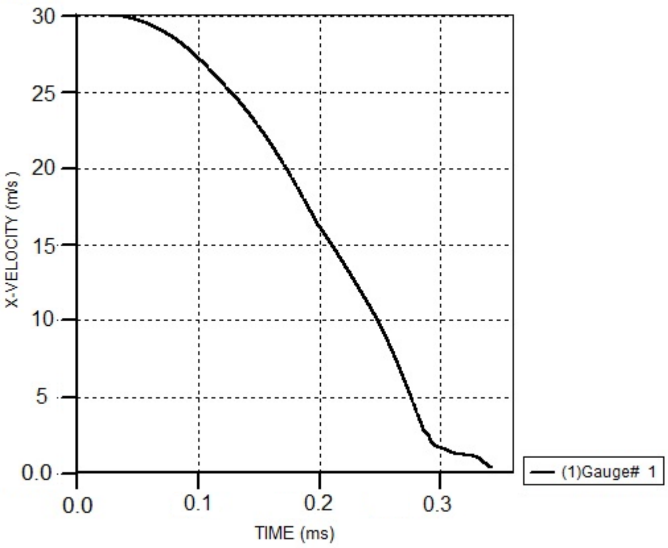

Fig. 6- The ballistics limited velocity graph of the bullet after collision with the four droplet samples from the simulation

In Fig. 6, the the ballistic limit of four dry layers is obtained 36 m/s which can be expressed as close to the result of the empirical test.

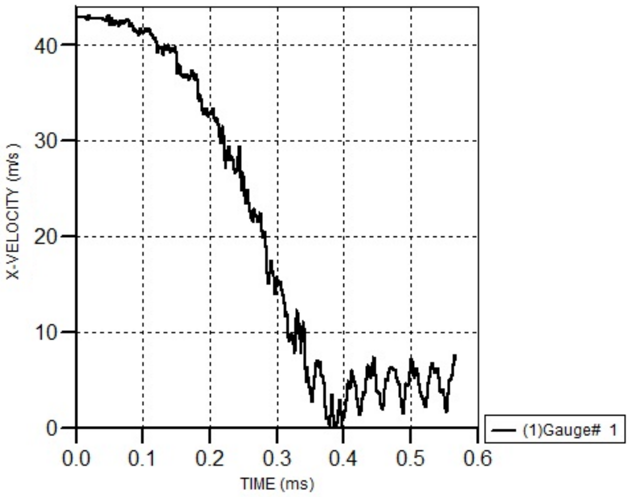

Figure 7- The ballistic limited velocity graph of the bullet after collision with a 15-STF simulated double-layered specimen.

Figure 7 shows the ballistic limit for a duplex specimen impregnated with 15% STF. Given the close-up of the obtained value, m / s44, with the experimental value (39.7 m / s), the result of the simulation can be deduced.

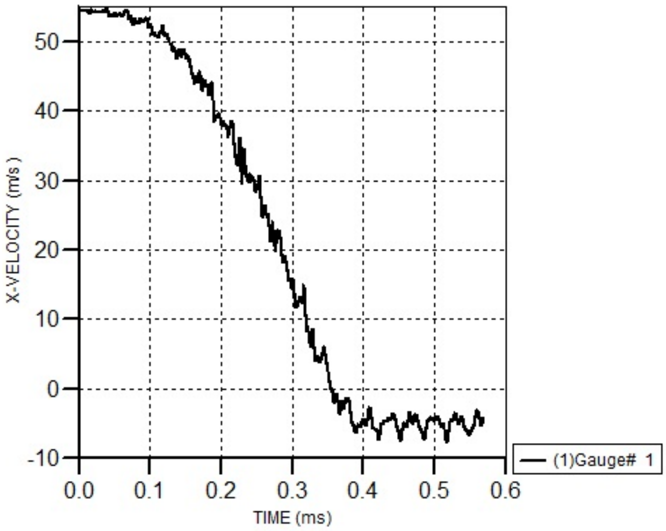

Figure 8- Ballistic velocity chart of the bullet after collision with the four-layer sample impregnated with STF 15% from the simulation

Figure 8 shows the graph of the simulation of the ballistic speed of the sample of four layers impregnated with STF% 15. Proximity of the simulation result 54 (m / s) with the experimental result 62.4 (m / s) indicates the correctness of the simulation

7. Conclusion

In non-Newtonian fluids, intermolecular force is much more complex than what Newton describes. With molecular force, you can predict the behavior of the material, but for non-Newtonian fluids, no prediction is feasible. In fact, non-Newtonian fluid is a fluid whose adhesion force changes, and it can almost be said that adhesion in these fluids can not be defined.

The impregnation of the fabric into the shear thickening fluid made the sample in ballistic experiments to have a higher ballistic velocity than a dry cloth and the energy absorbed by it would be higher. It therefore improves the fabric's ballistic properties.

In simulation experiments, the boundaries were simulated in such a way that the appearance of threads and fabric slip on the borders did not occur, but in the ballistic tests, the boundary conditions were between free and involved, and in the dry fabrics the threads emerged, and sometimes in Slippery fabrics occurred on the frontiers. Slipping at the boundaries increases the energy absorption, as the fabric slip on the boundary reduces the rate of strain increase in the fabric and even decreases the strain, which increases the penetration time, and thus the cloth can absorb more energy through the strain. On the other hand, there is a slip at lower speeds, as it is at higher velocities for longer penetration and, as a result, longitudinal and transverse waves have enough time to reach the boundary. The amount of fabric slipping on the border is larger when the size of the goal span is smaller, since the smaller the span of the target, the boundary should apply more to the longitudinal and transverse waves.

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