A Conceptual Design of an SMP Reinforced Knitted Spacer Structure for Ballistic Defense

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Abstract: A ballistic impact is a potential threat faced by military personnel in a battle-field, which includes fragmented munitions from explosive material. A wide array of material including woven structures, laminated structures and non-woven structures have been developed for protection against potential impacts. However, the kinetic energy of the bullet at the point of impact causes heat dissipation, which is an existing problem at hand when developing reinforcement material. Therefore, this research is focused on developing a conceptual model and design for a shape memory polymer reinforced knitted spacer structure, where the impact energy is to be absorbed by the polymeric yarn, when the thermal energy raises the temperature of the SMP above its glass transition temperature. A theoretical model has been developed to establish the fabric parameters of the structure to facilitate the purpose while, a comprehensive design methodology, including determining the SMPhas been introduced for the design of the ballistic protection structure. Additionally, a MATLAB simulation was conducted to model the relationship between thedissipated heat energy and the required fabric parameters.

Key words: Ballistic Protection, Shape Memory Polymers, Smart Textiles

1 Introduction

A ballistic encounter is an encounter or impact relating to the science of the motion of projectiles in flight. There is an array of potential ballistic encounters that a soldier may face in a battle-field. These include fragmenting munitions from tank-guns, rocket launches, field guns, mortars etc. These account for 60% - 80% of casualties on the battle-field. A large percentage of these fragments weigh less than 1g and have initial velocities of around 2000m/s. Protection from such ballistic encounters is defined as “Ballistic defense”. The bullets usually follow a trajectory path prior to the encounter. A bullet consists of a unique design that is inline with aero dynamics such that an extensive damage will occur to the surface upon impact.

A wide array of research has been conducted on the behavior of the bullets, the impact mechanism and ballistic protection material[1]-[6]. The impact strength and aero dynamics of a bullet have been thoroughly explored considering the weight, velocity, twist in the fire barrel, as the main factors[7]. The weight of a bullet is a function of its diameter, length, and composition of the bullet materials. Furthermore, bullet penetration and deformation are based on the angle of impact, the twist and the length of the firing barrel[7]. Perpendicular to the armor is the most critical angle to penetrate armor as all the kinetic energy of the bullet is concentrated on the pointed tip of the bullet and therefore it easily penetrates the layers of the armor. The projectile stability depends upon the spin it picks up when accelerating inside the firing barrel due to pressure, hence, higher the twist levels inside the firing barrel the higher the stability of the projectile. Thus, twist reduces the velocity of projectiles leaving the barrel, because part of firing energy is consumed by the friction in the barrel. When considering the length of the firing barrel, the longer barrel length holds the projectile longer and therefore the projectile gets higher acceleration. However, in a shorter barrel length, the projectiles accelerate only when they are in the barrel. One of the major contributing factors defining the bullet deformation or penetration capability is the velocity of the bullet[7]–[9]. Twist in the firing barrel provides the stability to the bullet when it is traveling in the air. Certain bullets wobble for a short distance after leaving the firing barrel due to the twist in the barrel.

Ballistic has two different meanings when it comes to fabric. First, it can mean the type of material used for soft body armor[7]. These materials are usually woven with high-strength fibers, such as a para-aramid, a high-performance polyethylene (HPPE) or high-modulus polyethylene. Those types of ballistic fabrics have a very specific end use, however. Lower-tech ballistic fabrics are those that are traditionally used in soft-sided luggage and backpacks. When considering the manufacturing of a ballistic material properties such as significantly higher tensile strength and modulus, lower fiber elongation, inherent resistance to chemicals, industrial solvents and lubricants have been prioritized. Literature presents instances where Gel spun HMPE fibers, PBO Fibers and Aramid Fibers have been used in this regard. These factors have been further optimized through changing the Polymer used to manufacture the fiber, the spinning process, the structural characteristics including molecular orientation and spinning direction and the effective cross-section area occupied by a single chain.

There are several fundamental principles that have been sourced through literature that have been used to evaluate the performance of a ballistic fiber. These include the strain velocity of ballistic fibers, which is the rate of strain dissipation through the axis of the fiber when the fiber is engaged with a high-speed projectile and the friction between fiber and fiber. The fiber friction properties along with the fiber physical properties play an important role in slowing down the projectile. According to literature, in existing ballistic materials, friction has been optimized by changing the fiber orientation, by applying coating on the fiber, bonding a film on the ballistic material and quilting[7].

Ballistic materials have been constructed using woven and non-woven material. In woven material the ballistic performance depends on, the physical properties of the ballistic fibers, denier of the fibers in warp and weft direction, level of twist in the yarn, weave design of the fabric, the damage to yarn during weaving operation and post weaving operations[7]. On the other hand, in non-woven material, this depends on the amount of intermingling of fiber within a yarn bundle, the spreading of the fibers at macro level, the type of resin, quantity of resin, and the bond between resin and fiber.

However, there are several limitations that exist in the existing developments for the ballistic material. These include, the heat dissipated from the impact causing damages and deformation to the material structure[10]–[14], limited data at high strain level encountered during projectile penetration, the mathematical models that have been developed so far are in early stages of evolution from linear materials to non-linear viscoelastic materials, hybrid materials proving difficult to calculate contribution of each material in defeating projectiles, and the complexity of the bullet deformation phenomenon[15]. Thus, investigating the feasibility of addressing the heat-dissipation issue through integration of an SMP yarn based spacer fabric panel behind the existing combat material, will be the focus of this research.

Incorporating a shock absorbent damping panel in front of the composite laminated (current) panel to successfully absorb the thermal energy and resist deformation, is suggested to be performed by incorporating a spacer knitted structure with a Shape Memory Polymer (SMP) based yarn[15], [16], used as the mono filament, that serves as the tucking yarn between the two beds, and as a Nylon and Spandex covered yarn in the two beds of the spacer structure.

2 Methodology

2.1 Modeling the Hypothesis

The energy absorbed or dissipated by the impact ‘E’ is such that,

$$E = \frac{1}{2}mv_i^2 - \frac{1}{2}mv_r^2 \tag{1}$$

Supposing, that the mass of the SMP yarns in the structure is ‘m’and the ‘c’ is the specific heat of the SMP yarn material, then if the temperature increment due to the thermal energy of the impact is $\Delta\theta$,

$$E = mc\Delta\theta + H \tag{2}$$

where ‘H’is the total of energy transformations other than thermal energy. Now if the temperature of the Shape Memory Polymer material is ‘T_0’and the initial temperature of the shape memory polymer is when the surrounding temperature is less than the glass transition temperature Tg, the SMP will originally be subjected to a deformation from the impact. However, at the point of impact due to the sudden temperature increment of $\Delta\theta$, if

$$Tg \le \Delta\theta \tag{3}$$

then a transformation will take place as the SMP returns to its original state, reinforcing the spacer structure.

2.2 The Conceptual Design

The structure is expected to be developed as a spacer knitted structure that is to be attached to a composite laminated panel for sufficient shock and heat absorbency.

Nylon, Spandex and Shape MemoryPolymeric yarn is suggested to be used to fabricate the conceptual design structure. The SMP yarn is expected to be prepared using a combination of BPDPA/ODA[17], whose molecular structure is presented below in Fig 2.

This polyimide is synthesized by polycondensation of bis phenol A dianhydride (BPADA) and 4,4′-diaminodiphenyl ether (ODA), and the aromatic polyimide chains possessing thermal stable but flexible linkages within the backbone act as the reversible phase of the shape memory process[17]. Moreover, the resultant shape memory polymer has and adjustable glass transition temperature ranging from 229 to 243 °C and shows excellent thermal cycling resistant properties. Also, the auto-ignition temperature of this polymer is at 510 °C at 1013 hPa°C[17], [18], thus validating its suitability to be used for this purpose.

The SMP yarn can be manufactured using melt spinning, there are several concerns however including, poor drying of the resin resulting in low viscosity, which in turn would cause foaming, flashing, and dripping of the nozzle[15]. To achieve optimum results, controlling the viscosity of the SMP in the nozzle of the extruder, while maintaining uniform melting of the polymer and strict temperature regulation and processing controls is required as the viscosity of the SMP is more temperature dependent. The process can be implemented using winding speeds between 10m/min to 50m/min and a laminar air temperature of 22 Celsius.

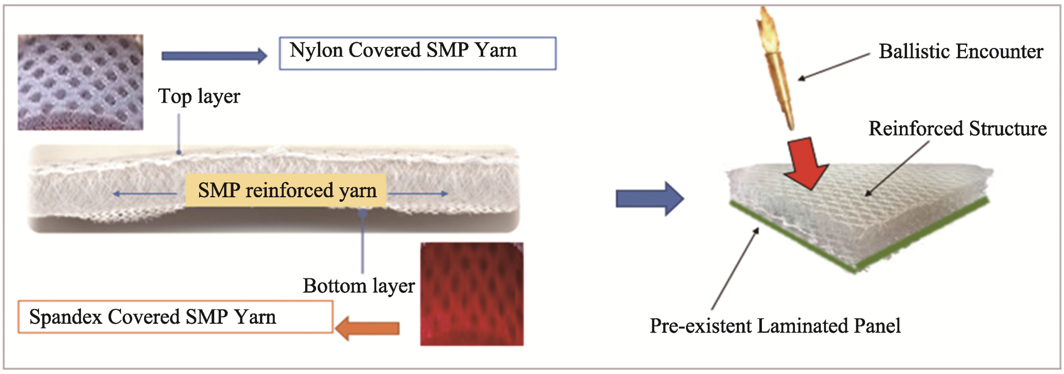


Fig.1 Conceptual Design of the SMP Reinforced Structure

The yarns for the Spacer structure are expected to be developed as covered yarn, as presented in the conceptual design using an air-jet spinning or core spinning yarn technique.The ballistic material can be prepared using a double bed knitting machine is required to facilitate production of both rib and interlock structures. The rib structure is expected to provide protection against medial impacts while the interlock structure provides against lateral impacts. The needle arrangement for the structures is as presented in Fig. 3.

2.3 Validation of the Conceptual Design

Considering the loop structure of a single lop of the knitted spacer structure as demonstrated below in Fig. 4 and the dimensions of the ballistic fabric can be considered as a length wise distance of a and a breadth of b, then the mass requirement of the SMP yarn can be calculated as follows.

$$Mass\ per\ knit\ loop = \left(\frac{\pi d^2 l}{4}\right) \times \rho \tag{4}$$

$$Number\ of\ loops = cb + wa \tag{5}$$

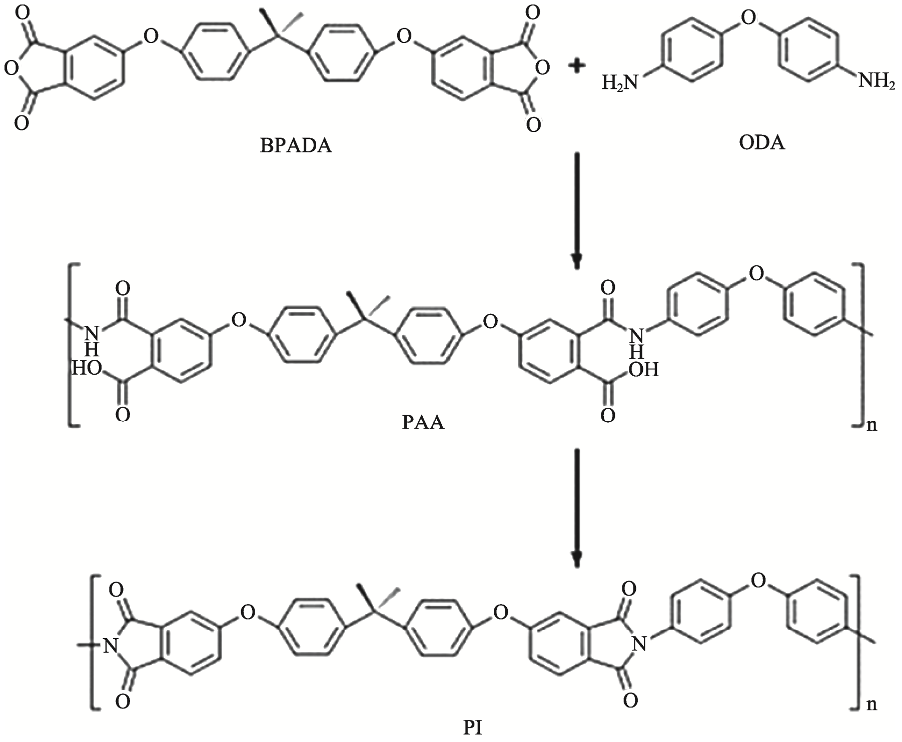
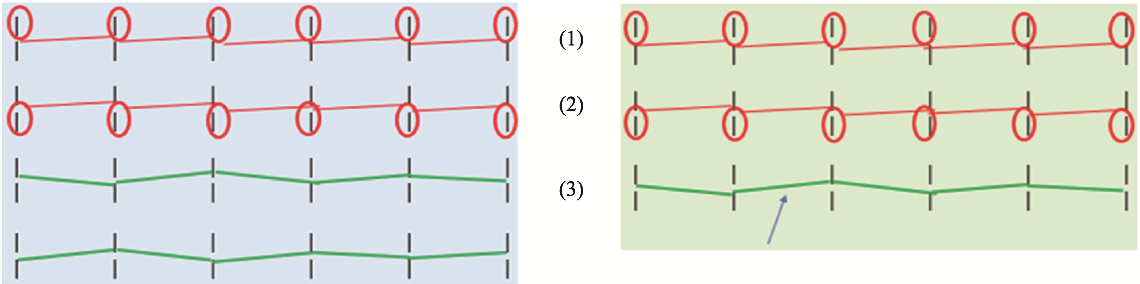


Fig.2 Synthesis of the Shape Memory Polyimide. BPADA and ODA Form Viscous Poly (Amic Acid)[17]



Needle arrangement requirement for Interlock Structure

Needle arrangement requirement for Rib Structure

Fig.3 Needle Arrangements of Rib and Interlock Structures for the Design

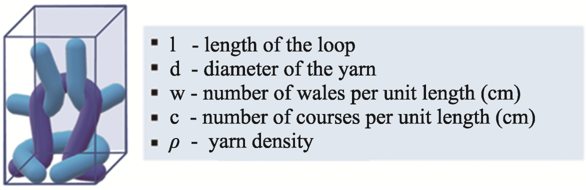


Fig.4 Three Dimensional Knitted Loop Structure

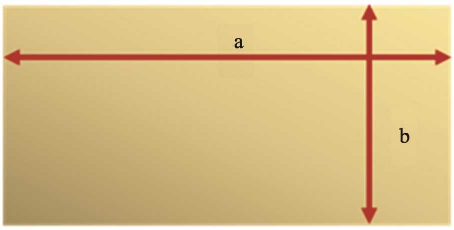


Fig.5 Dimensions of the Ballistic Fabric

As this is a double bed structure,

$$Mass\ of\ the\ loops = m = 2\times\left(\frac{\pi d^2 l}{4}\right)\times\rho\times(cb+wa) \quad (6)$$

when the,

$$Thermal\ Energy\ Absorbed\ by\ the\ Yarn = Q = mC\theta \quad (7)$$

$$m = \frac{Q}{C\theta} = 2\times\left(\frac{\pi d^2 l}{4}\right)\times\rho\times(cb+wa) \quad (8)$$

Hence, the yarn parameters and the fabric parameters can be adjusted such that, the mass requirement to absorb the above heat capacity is met. A MATLAB simulation of the required yarn mass using the identified SMP data, was conducted and the results are presented below in Fig. 6.

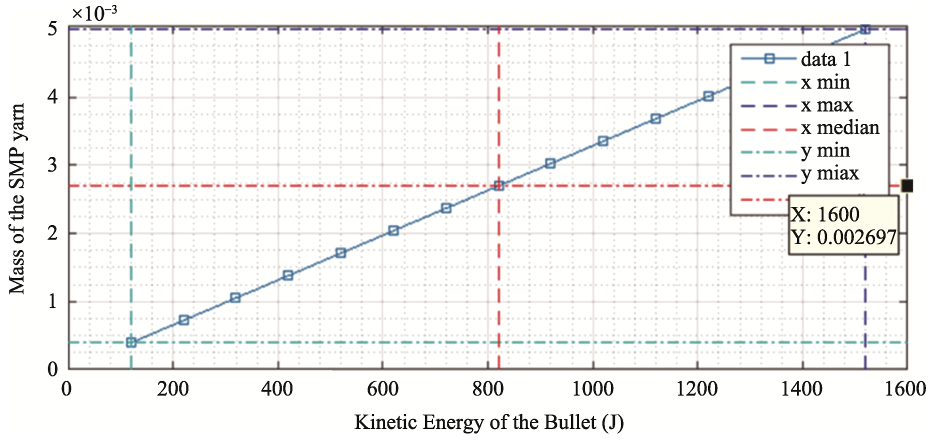


Fig.6 MATLAB Simulated Mass Requirement of the SMP Yarn

The SMP yarn can be characterized using the Shape fixity (SF), Shape recovery ratio (RR) and the Recovery stress. Additionally, the tensile storage modulus and the loss factor have been used in literature to characterize the behavior of the SMP yarns. The cyclic shape memory process of the SMP yarn can be further obtained to evaluate the hysteresis

Additionally, the impact performance of the ballistic fabric can be evaluated under the NIJ 0108.01 standard and the heat resistance as per ASTM D8101 standard.

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