Thin-Walled Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Impact response of Shear Thickening Fluid (STF) treated ultra high molecular weight poly ethylene composites – study of the effect of STF treatment method

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ARTICLE INFO

Keywords:
Ballistic
Shear Thickening Fluid
Impact
Composites
Impregnation
Body armour, ultra high molecular weight poly ethylene

ABSTRACT

Shear thickening fluids (STFs) are a special class of field responsive non-Newtonian fluids which exhibit transition from low viscosity to high viscosity state when these are subjected to shear deformation, particularly when the shear rate exceeds a critical value termed as the critical shear rate (CSR). Due to this unique characteristic of STFs, these are generally used for vibration mitigation or shock absorbance such as in vibration dampeners, hip protection pads, in protective gear for athletes etc. From the last two decades, STFs have found application in the field of ballistics, particularly in the development of special class of STF-intercalated armours called Liquid Body Armours (LBAs). These new age armours are lighter in weight and more flexible as compared to conventional heavy armours, which, infact seriously affect the mobility and agility of the soldier, especially in combat situations. Although, exhaustive studies are available which show the improvement in impact resistance of STF-treated high performance fabrics, but there are limited studies which explore the efficacy of STF treatment method. In this study, an attempt is made to understand this aspect. The low velocity impact studies were conducted on drop tower machine, while high velocity impact studies were accomplished on in-house designed and fabricated Split Hopkinson Pressure Bar (SHPB) experimental set-up. It was observed that when STF was kept in liquid form between layers of ballistic fabrics, the composite exhibited reduced performance, whereas, STF-treated ballisic composites exhibited enhanced impact toughness at high strain rates in SHPB testing.

1. Introduction

Ballistic protection is a class of protective clothing which is intended to protect the wearer from bullets, artillery shells, projectiles from small arms, steel fragments from hand-held weapons and exploding munitions [1]. Body armours from ancient times have been used to provide protection to humans against any threat or possible source of injury. These have been evolved from readily available materials such as animal skins or natural fibers made from cotton, thatch, silk woven in textile forms, to metallic shields of copper, steel or iron. In modern military operations, highly sophisticated weapons and ammunition as well as technology-driven war tactics have necessitated the development of advanced ballistic protection body armour systems that are damage resistant, flexible, light-weight, comfortable-fit and possess high energy absorbing/ dissipating capacity [2]. One of the widely adopted ways to enhance the ballistic performance of high strength materials is by impregnating it with STF (Shear Thickening Fluid) [3–9]. STFs are a special class of non-Newtonian fluids that possess the ability to undergo transition from low to high viscosity state under the imposed stress [6]. Recent innovations in the field of materials and manufacturing technology have led to the advent of superior manmade textile materials such as Kevlar, Spectra, Dyneema, Technora, Zylon, M5 etc. The tensile strength of these fibers is dictated by the molecular orientation of the polymer about the spinning direction as well as the degree of linearity of the polymeric chain. The last decade has witnessed the synergistic effect of STF and high performance fabrics, so as to produce a new, flexible and light weight material possessing superior knife, stab and ballistic resistant properties than the existing material systems [10–17]. In all the STF-treated ballistic materials an important parameter which dictates the ballistic performance of the hybrid structure is the method of STF treatment. The various parameters which strongly influence the efficacy of STF treatment are;

- Affinity of ballistic fiber or fabric towards STF, so that it is efficiently wetted and impregnated.
- The strength of the material which is used to hold the STF in a

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http://dx.doi.org/10.1016/j.tws.2017.04.025
Received 29 December 2016; Received in revised form 14 April 2017; Accepted 21 April 2017

ballistic composite structure.

- The optimal quantity of STF to be added to ballistic composite and the duration of STF impregnation.
- The lay-up sequence of ballistic composite to have appropriate number of STF-treated ballistic fabrics sandwiched between untreated layers.
- Effective method of STF treatment: This involves either placement of STF-filled high strength material pouches between ballistic fabrics or keeping STF treated ballistic fabrics between untreated layers.

There is a few available literature which explores the effect of STF packaging on the performance of ballistic composites. In 2013 Lukasz et al. [18] studied the effect of STF impregnation on the ballistic performance of Twaron® layers as well as by keeping a pouch made of Poly Ethylene filled with 50 g of liquid STF between 16 layers of Twaron®. From this study they inferred that Twaron® layers were weakened by STF impregnation, hence STF must always be kept separately from the ballistic fabric in order to enhance the ballistic resistance of the Liquid Body Armour [6]. In 2014 Adam et al. [19] from the same research group reported the use of STF in the inserts of the light weight bullet proof vests. From this study it was concluded that STF must be kept in a liquid form enclosed in a ballistic insert and placed firmly between layers of ballistic fabric, in order to enhance the ballistic penetration resistance of the bullet proof vest.

Thus from the limited literature available, there is no study which reports the effect of STF treatment method on the high strain rate behavior of ballistic composites. This article tends to study this aspect by evaluating the high strain rate response of STF treated ballistic composites using Split Hopkinson Pressure Bar (SHPB) technique. The objective of this study is to determine an effective STF treatment method so as to enhance the ballistic resistance of the resulting composite material. The STF treated composites were subjected to both low velocity impact testing on drop tower Instron machine as well as high strain rate testing on in-house designed and fabricated SHPB (Split Hopkinson Pressure Bar) apparatus, to establish the efficacy of STF treatment.

2. Materials and methods

2.1. Materials

(a) *For Synthesis of STF* – The materials used for STF synthesis include; dry Silica nano powder, Ethyl Alcohol and PPG (Poly Propylene Glycol). Rigid spherical silica particles of size 100 nm were procured from Nippon Shokubai, Japan. PPG having an average molecular weight of 400 g/mole, was chosen as the solvent for its high thermal stability, non-toxicity and easy availability. Ethyl alcohol was used as the solvent in ultrasonication process. PPG was obtained from Qualikems Fine Chemicals, whereas, ethanol was procured from Sigma-Aldrich. All the chemicals were used as received, without any further purification

(b) *For Synthesis of Extrusion Foamed Polymer Sheet* – CO15EG Impact Copolymer procured from Reliance Polymers was used for extrusion of porous sheet. It is a high impact Polypropylene (extrusion grade) with MFI (Melt Flow Index) of 1.8. CO15EG copolymer was compounded with Maleic Anhydride modified homopolymer Polypropylene OPTIM®P-425 which was procured from PLUSS Polymers, in order to enhance the wettability of CO15EG polymer with STF. The MFI of OPTIM®P-425 is 110 g/10 min as per ASTM D1238.

(c) *For Manufacturing of UHMWPE Composite Panels* – For manufacturing of composite panels, two variants of UHMWPE (Ultra High Molecular Weight Poly Ethylene)i.e. Gold Shield® and Spectra Shield® were procured from Honeywell, USA, in the form of 0/90 prepregs. Both the materials are patented products of Honeywell. Spectra Shield® composite panels were subjected to low velocity impact testing on drop tower machine whereas Gold Shield® panels were subjected to high strain rate testing on SHPB. This was done since Spectra Shield® is a laser-transparent material. Consequently, SHPB test specimens could not be cut from Spectra Shield® composite panel, whereas laser cutting of Gold Shield® panels was easily accomplished owing to its laser absorption characteristic.

2.2. Methods of Sample Preparation

(a) *Shear Thickening Fluid (STF)* – STF was synthesized by ultrasonic homogenization method. The known weight percentages of PPG and silica nano powder were mixed in excess amount of ethanol, and subsequently dispersed with high intensity ultrasonic horn (Ti-horn) at 20 kHz, 1200 W/cm^2 at amplitude of 42% for 3 h. The weight percentage of silica was kept fixed at 67.5% wt. After the ultrasonication process, the fluid sample was placed in a preheated oven at 80 °C for 2 h to evaporate the excess ethanol.

(b) *Extrusion Foaming of Polymeric Films* – CO15EG was compounded with OPTIM®P-425 in a twin screw extruder. The weight percentage of Maleic Anhydride Grafted PP (MAgPP) was kept fixed at 15 wt% in CO15EG. All the compounded pellets were dried at 60 °C overnight prior to extrusion.(Fig. 1 and 2)

The three crucial steps in continuous extrusion foaming process are; 1) formation of uniform polymer/gas solution 2) Cell nucleation and 3) Cell growth [20–22]. The attainment of a uniform polymer/gas single phase solution is essential for foaming since undissolved gas pockets tend to create large voids in the polymer matrix. In order to generate uniform polymer/gas solution, the injected gas must be below the solubility limit, and an effective diffusion technique should be em-

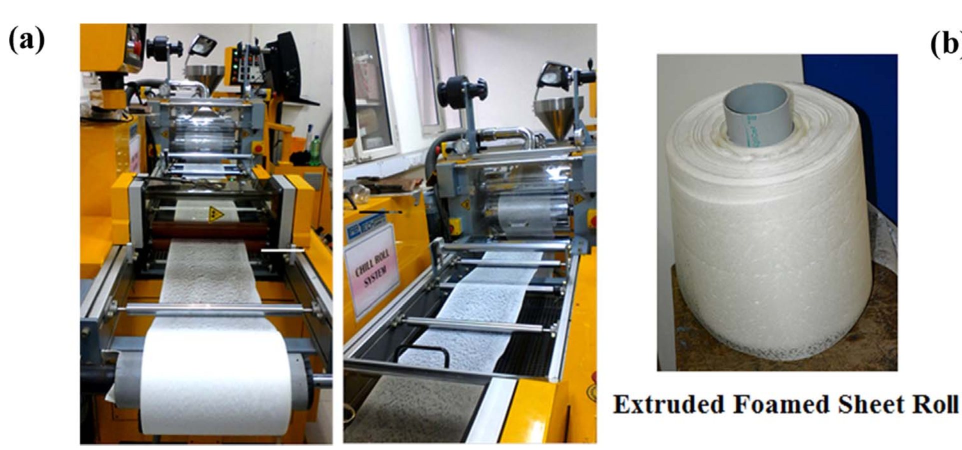

Fig. 1. (a) Pictures of continuous extrusion foaming of polymeric sheet (b) Extruded polymer roll.