International Journal of Impact Engineering 96 (2016) 11–22

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

The energy absorption behavior of hybrid composite laminates containing nano-fillers under ballistic impact

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ARTICLE INFO

Article history:
Received 27 November 2015
Received in revised form 15 March 2016
Accepted 18 May 2016
Available online 20 May 2016

Keywords:
Hybrid composites
Energy absorption
Ballistic impact
Protective armor
Nano-fillers

ABSTRACT

Hybrid composite laminates consisting of woven Kevlar fiber fabric, epoxy and AA 5086-H32 aluminum sheets were produced and the effects of addition of micro and nano-fillers to the fiber on ballistic response of the hybrid laminates were investigated. The micro and nano-fillers used in this study are powders of aluminum, gamma alumina, silicon carbide, colloidal silica and potato flour. They were introduced into the Kevlar fabrics by mixing with polyethylene glycol (PEG-400), followed by impregnation of the Kevlar fabric with the mixture and drying to eliminate the solvent. The energy absorption by the hybrid composite laminates containing the various nano-fillers under ballistic impact were determined and compared with laminate containing no nano-filler impregnation. The ballistic impact resistance of the produced hybrid composite laminates was tested according to NATO standards using a caliber 270 Winchester rifle. The projectile penetration and the resulting perforations of the hybrid laminates were studied in order to determine the influence of the deposited nano-fillers on Kevlar fibers on their energy absorption and impact resistance. The relationship between areal density and energy absorbed are discussed to determine which specimens perform better under ballistic impact. Protection levels achieved by targets were analyzed in relation to the initial impact energy from low caliber weapons. The results indicate that the ballistic impact resistance and impact energy absorption of the hybrid composite laminates were enhanced by deposition of micro and nano-fillers into surface of the Kevlar fibers fabrics. The highest impact energy absorption capacity was achieved by deposition of aluminum powder followed be colloidal silica and silicon carbide powder in that order. Addition of gamma alumina powder and potato flour has produced the least effect of enhancing the impact energy absorption capability of the laminates. These findings indicate that introduction of micro- and nano-fillers coating on Kevlar fabrics using PEG-400 is a promising method for strengthening interfacial bonding between the matrix and fibers in hybrid composite laminates.

1. Introduction

Improving the shielding capacity of protective armor materials against ballistic impact has continued to attract the interest of the scientific community. Development of hybrid composite laminate structures can offer a solution of providing protective shields that are lighter, leaner, and more potent than the conventional protective armor plates made of monolithic materials. Hybrid materials consist of layer of two or more existing materials configured in such a way that allows the superposition of their properties to meet targeted service requirements [1]. In hybrid composites, improved multilayer structures combining properties of widely diverse materials such as metal alloys, fibers, natural materials, and even nanoparticles are made possible in order to achieve protective armor with enhanced protection capability [2]. The motivation for the increased interest in the use of nanoparticles with dimensions ranging from 1 to 100 nm in engineering applications include their unique surface strengthening effect in metal alloys, ceramics, fibers, and even polymers leading to increase in mechanical properties such as strength and stiffness, and thermal properties, among others. Nanoparticles in low concentrations can achieve these purposes without compromising the density, toughness or the manufacturing process [3–5].

Most of the studies on armor vests used in ballistic protection have reported ways of improving the resistance of Kevlar fibers to ballistic impact failure. One of the most common ways of achieving this is through impregnation of the Kevlar fabrics with shear thickening fluid (STF). STF consists of oxide particles suspended in a liquid polymer. It behaves as a non-Newtonian fluid whose viscosity increases when shear stress is applied. The components of STF are polyethylene glycol and colloidal silica. STF assumes a solid-like behavior at the moment of impact loading. After impact loading, they return to their fluid state [6,7]. Colloidal silica particles create

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http://dx.doi.org/10.1016/j.ijimpeng.2016.05.012
0734-743X/

a sealing coat, which enhances the resistance of the woven fibers to ballistic impact. Infiltration of aramid fiber fabrics with STF results in a microstructural change as the colloidal silica in the STF create particle clusters (hydro clusters), which enhance the hydrodynamic stress in the suspension and increase the capacity to resist ballistic impact [8,9]. Experimental investigations have proved that the resistance of Kevlar fabrics to ballistic penetration is improved by impregnation with silica particles (size 450 nm) dispersed in ethylene glycol. In addition, it was established that this impregnation enhanced the material flexibility and reduced the required thickness for adequate protection when compared with Kevlar fabrics with no STF-impregnation [10]. According to Majumdar et al. [8], the higher the STF concentration, the better the capacity for impact energy absorption by fibrous materials, and the lower will be the number of fiber layers required for the needed protection. STF increases the friction between the yarns during ballistic impacts and reduces the number of Kevlar layers used in composite laminates by between 40 and 80% [11]. About 50% increase in energy absorption capacity was reported when Kevlar was impregnated by STF in comparison with composites made of Kevlar fabric that is not treated with STF [12].

In another study, the use of aluminum oxide (Al_2O_3) nanofillers in epoxy resin reinforced with Kevlar 29 fabrics was reported to improve the performance of bulletproof vest made of this composite material. Composite plates of different thickness were used to show the level of energy absorption by each plates during ballistic impact testing. The results showed that by using a stacking sequence of 30 layers cross–ply laminates, the highest energy absorption was achieved with an impact velocity of 400 m/s [13]. In the same way, epoxy resin filled with oxide nanoparticles of silane modified iron (III) was impregnated into Kevlar fibers to create reinforced composite laminates; the oxide nanoparticle impregnation resulted in a significant enhancement of the tensile strength of the laminates [14]. Also, Kevlar fibers impregnated with epoxy resin filled with cork powder, cork/clays, and clays were compared with specimens made of epoxy resin reinforced with Kevlar. Previous research findings indicated that addition of cork powder to polyester resin reduces the flexural strength, and that the addition of the fillers can change the mechanical behavior of the matrix. However, for both kinds of specimens, similar fatigue strength was observed [15]. In another experiment, the results indicated that fillers impregnation enhances the impact resistance by 4.5% for laminates filled with cork, by 10.4% for laminates filled with cork/clay and by 16.1% for laminates filled with clay [16]. When carbon fibers were coated with carbon nanotubes as nano-fillers in an epoxy resin, the fiber surface area increased, which provided a stronger interfacial bonding between the CNT/carbon fiber/epoxy matrix [17–19]. Hybrid nanocomposites developed using different configurations of fiberglass/epoxy/nano-clay and fiberglass/epoxy/nano graphene were subjected to ballistic impacts from 38 and 9 mm caliber pistols, and the results showed that hybrid nano-composites are able to absorb impact energy ranging from 284 J to 446 J, and that nano-clay and graphene additions into the epoxy matrix increase the energy absorption capacity of the hybrid nano-composites [20].

In another study, woven carbon fibers were reinforced with a polymer/epoxy matrix containing dispersed short multi-walled carbon nanotubes and significant improvement in inter-laminar damage tolerance was achieved with the carbon nanotubes addition (0.5 wt. %) to the epoxy matrix. The static interlaminar shear strength of the hybrid composite was found to increase by 20%, and interlaminar fracture toughness (Mode I) by 180% in relation to the samples without nano-reinforcement [21]. In an effort to improve the impact resistance of a carbon fiber reinforced plastic (CFRP), about 0.5% by weight of multi-wall carbon nanotubes (MWCNTs) were dispersed in the epoxy matrix (Bisphenol A). The MWCNTs inclusion enhanced the fracture resistance and ballistic impact performance (energy absorption capability) of the CFRPs [22]. Addition of carbon nanotubes (CNTs) and nano-sized core shell rubber particles (CSR) to Kevlar fiber reinforced epoxy also led to improvement in impact energy absorption capacity [23]. Different techniques of nano-particles' dispersion have been employed to enhance interfacial bonding between matrix and fibers. For example, CNTs particles were impregnated directly on carbon fibers through immersion in an aqueous suspension prepared with CNTs, which led to better results compared to that other dispersion techniques such as CNTs mixed with epoxy resin or spraying methods [24].

Although many studies have been conducted on the effects of STF, CNTs, and Al_2O_3 impregnation into the resin matrix of fiber reinforced plastics on their ballistic impact resistance. However, there is no information on the ballistic impact response of hybrid composites plates consisting of aluminum alloy, epoxy and Kevlar fabrics impregnated with other nano-fillers. It is very important to determine whether nano-fillers impregnation into fibers will allow such hybridization with metallic layers to produce high performance protective armor. In this study, nano-fillers of silica carbide, aluminum powder, colloidal silica, gamma alumina, and potato flour were mixed with a solution of polyethylene glycol (PEG-400) and were then infiltrated into Kevlar fabrics in order to improve the energy absorption capacity of the resulting hybrid composite laminates. This is a new infiltration method of micro and nano fillers into fabric fibers and the feasibility of deposition using polyethylene glycol (PEG-400) will be evaluated. The objective of this study is to improve the ballistic impact resistance and toughness of the hybrid composite laminates by addition of these nano-fillers to reinforce the Kevlar fiber components without significantly altering the material's physical properties such as weight, thickness or density. The capacity of the obtained hybrid composite laminates to absorb energy, as a function of the type of the applied nano-fillers was determined by conducting ballistic impact testing using a 270 caliber Winchester rifle and 150 gr power point ammunitions with an average mass of 9.72 g.

2. Material and experimental procedure

2.1. Materials

2.1.1. Aluminum alloy AA 5086-H32

The hybrid composite laminates were built using AA 5086-H32 aluminum alloy sheet, supplied by Onlinemetals.com (US), as the metallic component. The aluminum alloy sheets have a thickness of 1.6 mm and a nominal chemical composition of 95.4 Al, 0.05–0.25 Cr, 0.1max Cu, 0.5max Fe, 3.5–4.5 Mg, 0.2–0.7 Mn, 0.4max Si, and 0.25max Zn. The primary role of the AA 5086 aluminum alloy sheet is to act as rigid plates that support the fibrous materials and keep them in their relative positions within the hybrid laminates. They can also help to hinder propagation of crack through the fibers and protect the fibers from the environment. The aluminum plate will enable uniform distribution of impact loads and enhance impact resistance of the laminates.

2.1.2. Kevlar fibers 49

The Cross-ply woven Kevlar fiber 49 (#281-38) fabric used in this study was supplied by Aircraft Spruce Canada. The fabric has a thickness of 0.25 mm and a mass of about 169.8 g/m^2. The role of the Kevlar fibers is to act as reinforcement and enhance the mechanical properties such as tensile and flexural strength of the polymer matrix. Their high tensile strength prevents significant stretching and deflection of resultant composite materials during ballistic impacts. These fibers slow down the projectile penetration through the initial tensile elongation, inter-laminar delamination and fiber pullout. In addition, their high strength and elastic modulus enhance