



Novel ballistic ramie fabric composite competing with Kevlar™ fabric in multilayered armor



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ABSTRACT

It was reported recently that the most important function of a polymeric backing plate in multilayered ballistic armor system (MBAS) is capturing the post-impact debris coming from fragmented front ceramic tile. Following this discovery, conventional Kevlar™ fabric was replaced in this study with a 30 vol.% ramie fabric – reinforced epoxy composite and underwent ballistic tests with 7.62 mm ammunition. Multiple tests with a clay witness (simulating a personal body) revealed a 10–20% smaller depth of indentation made by penetrating projectiles in MBAS equipped with a novel ramie – epoxy composite backing plate as compared to Kevlar™ fabric. The massive capturing of ceramic fragments was observed for both the Kevlar™ fabric and ramie – epoxy composite, although the novel composite dissipated 3 times more energy during the process. Impedance-matching analysis corroborates the ballistic performance results. The 95% cost reduction indicates a substantial economic advantage of the ramie – epoxy composite over Kevlar™.

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1. Introduction

In a ballistic backface signature test, the NIJ standard for personal protection [1] requires that a projectile to be stopped and the penetration depth of depression (indentation) into a clay witness (backing the armor) should not exceed 1.73 in. (~44 mm). Deeper penetrations are associated with lethal trauma inflicted to the wearer. Therefore, the smaller the indentation, the better the armor ballistic performance should be. Lee et al. [2] reported that a 1.4 mm thick stack of Kevlar™ woven (aramid fabric composite) is able to stop the low velocity projectiles (~250 m/s) with a related indentation of ~21 mm in the clay witness. In these ballistic tests, the authors observed aramid fiber stretching and breakage near the impact point, together with yarn pull-out. Indeed, Kevlar™ woven fabric (Kevlar™ for short) is worldwide recognized as one of the most effective single composite material for personal body armor protection against low (level I) and medium (level II) velocity ammunition (<500 m/s). For high velocity projectiles such as level III caliber 7.62 × 51 mm NATO ammunition (~850 m/s), Kevlar™ alone is not sufficient to protect armor wearer from injuries unless a very large (impractical) thickness is used that significantly limits wearer mobility. Against 7.62 mm ammunition, a multilayered ballistic armor system (MBAS), composed of a front ceramic tile and

backed by a plate of fiber-based material such as Kevlar™ or laminated ultra-high molecular weight polyethylene [3] is preferred for light-weight body vests. The hard ceramic dissipates a great percentage of the projectile impact energy by means of its deformation, shattering and erosion. Moreover, the shock wave impedance mismatch between the front ceramic and the lower density backing plate generates a reflected tensile shock wave, which causes fragmentation of the brittle ceramic [4]. The role of the backing plate is to further reduce the kinetic energy of fragments.

In a recent experimental work [5], the main energy absorption mechanism provided by the Kevlar™ (as the MBAS front ceramic backing plate against a 7.62 mm projectile) was found to be through capturing the fragments onto aramid fibers through mechanical incrustation and the involvement of surface forces. It was also reported that the projectile/ceramic fragmentation dissipates ~57% of the impact energy and the backing Kevlar™ plate captures ~38% impact energy [5]. By contrast, the same Kevlar™ plate arranged as a single target in a similar ballistic test dissipates <2% of the impact energy [5]. Two practical outcomes conclude previous research. First, the Kevlar™ is 20 times more ballistic effective in a MBAS than alone against the impact of a high velocity projectile. Second, based on the experimental percentage of dissipated impact energy by a 10 mm thick plate, a monolithic armor vest for body protection would require a Kevlar™ thickness with more than 50 mm to stop a 7.62 mm projectile. One then hypothesizes that the superior strength and stiffness of the Kevlar™ in a MBAS may not be as important as its capacity to collect ceramic fragments.

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If our hypothesis is correct, the Kevlar™ backing plate could be replaced in MBAS with less expensive fabric of similar yarn characteristics. Selecting fabric made of relatively stronger fibers and high yarn density could, most likely, even improve the performance of the MBAS backing plate. In this work, it is statistically shown that a polymer composite reinforced with a fabric made of natural fiber of ramie plant has a better ballistic performance than Kevlar™. This fabric made of natural fibers and designed for MBAS is environmentally sustainable and much cheaper than Kevlar™. The latest reviews [6–9] indicate that several natural fibers display favorable mechanical properties and are replacing traditional synthetic reinforcements in composites, including those used in armors [10].

The objective of this study was to test the ballistic performance of a novel epoxy composite reinforced with 30 vol.% of ramie fabric as a possible substitute for Kevlar™ in the second layer for MBAS with front ceramic tile. In comparison to aramid fiber with density of 1.44 g/cm³, tensile strength ranging from 3,600 to 4,100 MPa and Young's modulus of 151 GPa [11], the ramie fiber has a comparable density of 1.5 g/cm³ but lower tensile strength range of 400–1,620 MPa and Young's modulus between 61 and 128 GPa [6]. Epoxy composites reinforced with 30 vol.% of continuous ramie fibers demonstrate even lower tensile strength of 69 MPa and an elastic modulus of 1.5 GPa [12] as well as Charpy impact energy of 212 J/m [13]. Marsyahyo et al. [14] also reported that bulletproof panels made of ramie woven reinforced epoxy composites are able to resist projectiles up to NIJ level II. Their composites were neither backface signature tested as second layer in MBAS nor was the fragment collecting ability was assessed. In the present work, the function played by the ramie composite in MBAS is also discussed in details.

2. Experimental procedure

Ballistic tests were conducted with MBAS targets composed of a front 10 mm thick Al₂O₃ doped with 4 wt.% N₂O₅ ceramic backed by a 10 mm thick plate of either 30 vol.% of ramie fabric reinforcing an epoxy matrix composite (ramie composite for short) or Kevlar™. The ramie fiber was a threaded woven using natural fibers extracted from the stem of the plant *Boehmeria nivea* (Fig. 1). Fig. 2 illustrates both the Kevlar™ single ply and the ramie fabric. The Du Pont Kevlar™ (aramid woven fabric and 5% polychloroprene laminate composite) with areal density of 460 g/m² was supplied by LFJ Blindagem (Brazil). The ramie fabric with areal density of 245 g/m² was purchased from the Rose Natural (China). Fig. 2 also shows the microstructure of Kevlar™ and ramie fabrics with tight weaving.

The Dow Chemical epoxy resin (diglycidyl ether of the bisphenol-A (DGEBA) with triethylene tetramine (TETA) as hardener) was supplied by Resinpoxy Prod. Quim. (Brazil). Square plates with 150 × 150 mm with a thickness of 10 mm were fabricated for both Kevlar™ and the ramie composite. The Kevlar™ plate was made of 18 plies. Ramie composite plates were manufactured by intercalation of 10 fabric pieces, corresponding to 30 vol.% of fabric (Fig. 2b) and fluid DGEBA/TETA epoxy inside a steel mold. This laminate composite was cured at a room temperature at a pressure of 0.53 MPa for 24 h.

MBAS targets were produced by bonding the front ceramic and its backing plate (Kevlar™ or ramie composite) to a 5 mm thick 5052-H34 aluminum alloy sheet that was supplied by the Metalak Co. (Brazil) with Ultraflex™ (polyurethane) adhesive. Before testing, a block of Roma type clay witness supplied by the Corfix Ltda., (Brazil) was placed behind the target in direct contact with the aluminum alloy sheet. Fig. 3 schematically illustrates MBAS targets used in the ballistic test. All the ballistic tests, as per the NIJ standard [1], were carried out at the Brazilian Army shooting range facility (CAEX, Rio de Janeiro, Brazil) using 7.62 × 51 mm NATO ammunition. Fig. 4 shows a schematic of the ballistic system with a gun barrel from which the 9.7 g projectile is propelled towards the target located 15 m away. Optical barrier and Doppler radar, also shown in Fig. 4, measured the projectile velocity.

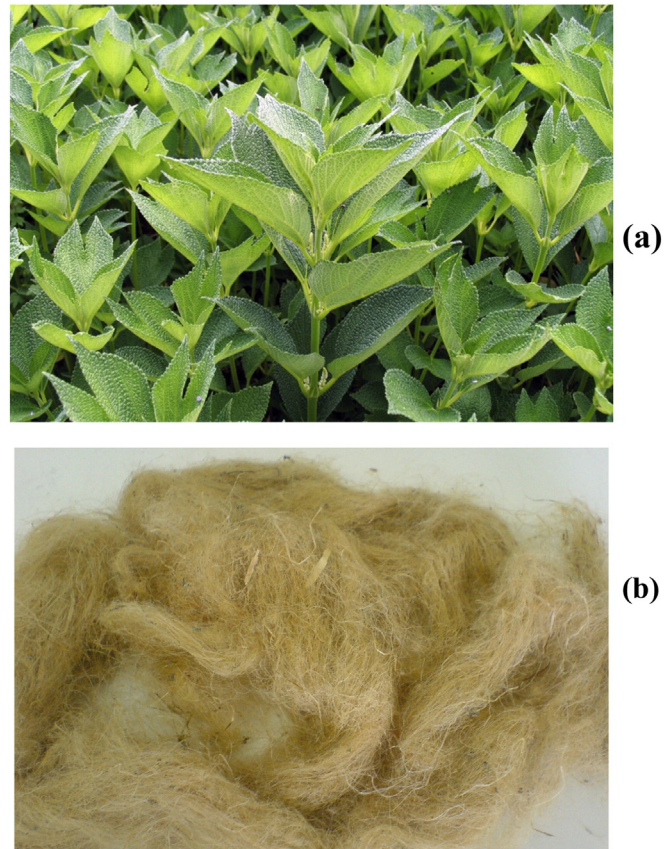


Fig. 1. Ramie plant (a) and bundle of extracted fibers (b).

The clay witness indentation was measured with a special Mitutoyo caliper of 0.01 mm accuracy. The caliper wings were placed on the plane surface of the clay block near indentation rim. This plane surface was set as the caliper baseline for depth measurements.

A total of 15 MBAS targets with Kevlar™ and 10 ramie composite MBAS targets were ballistic tested, and the depth of penetration results, a minimum of 10 indentation measurements per indentation, were analyzed by the Weibull statistical method.

The Weibull Analysis program uses the cumulative distribution function:

$$F(x) = 1 - \exp \left[- \left(\frac{x}{\theta} \right)^\beta \right] \quad (1)$$

where x corresponds to the depth of indentation and the parameters β and θ are the Weibull modulus and characteristic indentation, respectively. By applying a double logarithm, a linear expression allows the graphic interpretation of the Weibull parameters:

$$\ln \ln \left[\frac{1}{1 - F(x)} \right] = \beta \ln x - (\beta \ln \theta) \quad (2)$$

Impedance matching of the impact wave propagating in the MBAS front ceramic and reflecting at the backing plate was evaluated to compare the energy dissipation efficiency of Kevlar™ and ramie composite. According to Meyers [15], the shock wave impedance is defined as:

$$Z = \rho_0 U_s \quad (3)$$

where ρ_0 is the material density and U_s the wave velocity inside the material. The value of Z was calculated by impedance matching at the

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