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High strain rate compression response of woven Kevlar reinforced polypropylene composites

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ABSTRACT

In this study, experimental investigations on Kevlar fiber reinforced polypropylene (PP) woven composites under high strain rate compression loading are discussed. Kevlar/PP composite laminates with 8 and 24 layers are fabricated using vacuum assisted compression molding technique. Maleic anhydride grafted-PP (MAg-PP) is added to PP to improve the interfacial property between Kevlar fiber and PP resin. The through-thickness properties at high strain rates from 1370 to 6066 s^{-1} are obtained using split Hopkinson pressure bar (SHPB) setup. The behavior of PP resin is found to be different than the commonly used thermoset resins, such as epoxy. Dynamic stress–strain relations are drawn to reveal the mechanical properties at high strain rates and these relations appear to be rate sensitive. As a result, the peak stress increased by three times, toughness increased by almost ten times and strain at peak stress increased by as much as two times with an increase in the strain rate. The final failure of the specimens is examined by scanning electron microscopy (SEM) to explore the possible failure mechanisms such as, delamination, fiber failure and shear fracture.

1. Introduction

Composite materials possess high specific strength and specific stiffness with less fatigue. Due to this advantage of composite materials, it's been widely used in military, aerospace and other structural applications where weight of the structure is a significant parameter. Composite structures undergo different loading conditions, such as, static and dynamic loads during their service life.

When the composite laminate is used as a body armor material, the armor undergoes dynamic loading when projectile impacts the target [1]. Among all the composite materials, Kevlar finds its major application in body/vehicle armors as it exhibits an improved impact resistance with lightweight. As the necessity increases, it is very important to understand the effect of high strain rate on the impact performance of Kevlar composite laminates. The response of the material under different strain rates should be clearly known for the effective use of materials [2]. Through-the-thickness loading is one of the crucial condition in the ballistic impact applications. The compressive properties of composite armor materials under high strain rate conditions are highly desirable to assess the ballistic impact response.

Composite materials have been extensively characterized under quasi-static tensile, compressive and shear loading conditions [3,4]. However, understanding the mechanical behavior of these materials under dynamic loading conditions is limited due to the associated technical hitches at high strain rates. Most widely used technique to characterize the materials at high strain rates is a split Hopkinson pressure bar (SHPB) [2,5–7]. Recent works on the high strain rate behavior of polymer composites were based on the thermoset-based laminates made from glass and carbon fibers [8–15]. Few works [7,16–19] reported on the dynamic compressive response of Kevlar composites majorly based on the thermoset-based matrix.

Woo et al. [7] used an acoustic emission technique to characterize the failure progress in Kevlar/epoxy composites under high strain rate impact. The peak stress and toughness of the Kevlar-woven fabric specimen were increased almost two times, with an increase in strain rate in the range of 1182–1460 s^{-1}, whereas the strain at peak stress decreased by approximately 16%. An experimental investigation was carried out by Daniel and Liber [16] to assess the strain rate dependence on the tensile behavior of Kevlar/

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epoxy at a strain rate up to 27 s^{-1} on the modified universal testing machine (UTM). It was observed that, with an increase in strain rate, modulus and strength of Kevlar/epoxy increased. Dynamic response of Kevlar/Polyester composites was investigated by Harding and Welsh [17] for cylindrical projectile up to a strain rate of 400 s^{-1}. They found that the tensile modulus increased within the strain rate range from 10^{-4} to 10^{3} s^{-1} and reported the non-linear response in dynamic tension. Zhu et al. [18] carried out static and dynamic tests on Kevlar/polyester laminates. The damage pattern observed for dynamic loading was different than that of the corresponding quasi-static case. Jacob et al. [20] carried out a detailed review of the strain rate dependence on the mechanical properties of polymer composites and a lot of contradiction in the data, regarding the strain rate effect was reported.

From the above literature, it is evident that the mechanical properties of the fiber reinforced composite laminates are sensitive to strain rate. Numerous studies have been conducted to characterize the mechanical properties of Kevlar fibers [19–22] and Kevlar fabrics [23]. Wang and Xia [19,21] investigated the influence of strain rates (10^{-4} to 10^{3} s^{-1}) and temperature(−60 to 90 °C) on Kevlar 49 fiber bundles. Results show that the mechanical properties of Kevlar 49 fibers are sensitive to strain rate and temperature. It was also reported that at a constant temperature, initial elastic modulus, strength, and failure strain increase with an increase in the strain rate, and for a fixed strain rate, the initial elastic modulus decreases and failure strain increases with increase in test temperature. The experimental investigation of Lim et al. [22] included three high-performance fibers (Kevlar, Kevlar 129, and Twaron) fabricated at different times over a period of ten years. Their experimental results show that longitudinal tensile strength of the fibers weakly dependent on the fiber gage length and reported the insignificant strain rate effect on tensile strengths (only by a few percent). Tensile tests of Zhu et al. [23] on Kevlar 49 plain weave fabric at strain rates ranging from 25 to 170 s^{-1} reported that the dynamic material properties in terms of Young's modulus, tensile strength, maximum strain and toughness increase with an increase in the strain rate.

There is a lack of experimental studies on the composite laminas made from Kevlar fibers reinforced with a thermoplastic resin. The majority of the works reported in the literature were concentrated on the high strain rate behavior of thermoset-based composite laminates. Limited research has been reported on the dynamic response of thermoplastic-based Kevlar composites [24,25]. Rodriguez et al. [24] examined the effects of high strain rate on polyethylene and aramid woven fabrics. They deduced from their results that dynamic stress–strain curve is more linear as compared to the static one. Dynamic compression tests and quasi-static tests of Viswanathan et al. [25] on Kevlar 29/polyethylene showed significant increase in the tensile strength and decrease in failure strain at high strain rates as compared to that of the quasi-static tests. Carillo et al. [26] reported that the addition of polypropylene (PP) to aramid (Kevlar 129) fabrics shows improved impact resistance. However, low adhesion was reported between aramid fabrics and PP matrix. There is no consistent data available for the characterization of dynamic response of thermoplastic-based composite laminates made from Kevlar fibers and PP matrix. To the best of the author's knowledge, the compressive properties of Kevlar fiber reinforced thermoplastic composites in the through-thickness direction at high strain rates have not been reported in the open literature.

In the present study, the through-thickness compressive properties of thermoplastic-based composite laminates made from Kevlar fiber and maleic anhydride grafted-PP (MAg-PP) matrix are reported at high strain rates ranging from 1370 to 6066 s^{-1}. Grafted maleic anhydride-PP is added to PP resin to improve the adhesion between Kevlar fiber and PP resin. Kevlar/MAg-PP (K-MPP) composite laminates consisting of 8 and 24 layers are fabricated using vacuum assisted compression molding machine. High strain rate compressive properties of the K-MPP composite laminates with respect to through-the-thickness direction are characterized using SHPB. The compressive stress–strain behavior, toughness, compressive peak stress and strain at peak stress are studied for the fabricated composite laminates. Following the experiments, failure mechanisms are characterized through scanning electron microscopy (SEM).

2. Experiments

2.1. Fabrication of composite laminates

Kevlar 29 yarns with 1000 denier were woven into plain woven fabric with areal density of 364 g/m^2. Yarns made of thousands of fibers, were woven into this fabric. The yarn tenacity was 14.91 g/den with 40 ends/inch in both weft and warp directions. Thermoplastic polymer PP was selected as matrix due to its lightweight and density of 0.855 g/cm^3. The interfacial property between Kevlar fabric and PP was improved by adding a coupling agent called, maleic anhydride grafted PP (MAg-PP). The main function of this coupling agent is linking of fibers to the polymer matrix and reducing the pull out while increasing the impact and tensile strength. Kevlar/MAg-PP (K-MPP) composite laminates were fabricated using vacuum assisted compression molding machine. PP sheets were coated with grafted maleic anhydride (MAg) to improve the interfacial property between Kevlar and PP resin. The alternate layers of Kevlar fabric and MAg-PP sheets were stacked and placed in the vacuum chamber containing flat plate molds. The fabric weave pattern and stacking sequence of the preform are shown in Fig. 1. The specimens were heated at a temperature of 200 °C under 10 bar pressure and cooled to room temperature. The matrix (MAg-PP sheet) thickness was 0.05–0.1 mm and the Kevlar fabric thickness was 0.15–0.2 mm. To avoid formation of voids during the fabrication process, a vacuum was maintained at 550 mm of Hg in a vacuum chamber. K-MPP laminates with 8 layers (1.6–1.7 mm thick) and 24 layers (4.3–4.6 mm thick) were cut out from a square plate of 160 × 160 mm, through laser cutting to prepare the test specimen for dynamic characterization (Fig. 1). The fiber volume fraction was measured through burn off test according to ASTM-D-2584-02 and it was observed to be 50–57%.

The critical slenderness ratio (l/d) is imperative to ensure that the results obtained from the experiment reflect the desired material properties. Inertial effects produce stress waves along the radial and the axial directions of the specimen. If the ends of the specimen are well lubricated, it minimizes the inertial effects. The correction for friction depends on the l/d ratio of the specimen. The l/d ratio of 0.3–0.5 was shown to be good criteria of SHPB specimen design [27]. However, it was also suggested that the tests on the materials with high flow stress and low density are less prone to such inertial errors [28]. As the material used in the present study is of low density, low l/d ratio was considered to avoid inertial effects. The diameter of the specimen was considered in the range of 15.5–16 mm. Length of the specimen was governed by the thickness of the laminate which comes out to be approximately 1.6–1.7 mm for 8-layer specimens and 4.3–4.6 mm for 24-layer specimens. Therefore, the l/d ratio of the present specimens was in the range of 0.1–0.3.

2.2. High strain rate test

High strain rate experiments were performed using SHPB apparatus available at Impact Mechanics Lab, Department of