A COMPARISON OF PENETRATION MECHANICS OF METAL AND FIBER/RESIN COMPOSITE TARGETS AGAINST BALLISTIC IMPACT

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Introduction

In designing armor, materials high hardness, strength, and toughness have traditionally been sought, since common sense would dictate that such materials should be most resistant to attack by a projectile. However, according to Shockey et al. [1] ballistic tests often show that the best-performing armor material is not necessarily the strongest, the toughest, or the hardest. To understand this difference between the common sense and the test results the armor development should not be looked at from the perspective of conventional bulk properties but from that of micromechanical mechanisms. An understanding of the mechanisms operating in a target during a penetration event can suggest microstructures that are more resistant to penetration and that will lead to protective materials with better performance.

Penetration mechanisms are perhaps best revealed by post-test examination of penetrated targets. Ejected or otherwise separated target material contains telltale signs of failure modes that occur during penetration, as does the material in the vicinity of penetration cavity. The collection of loose material and the sectioning of penetrated material, followed by unaided visual inspection and inspection under the microscope, show the damage features, helping to uncover the mechanisms of material failure.

Penetration and failure in metal plates

Metals are isotropic materials i.e. having same properties in all directions. Models of penetration and perforations are based on laws of conservation and compatibility. As an impact occurs, the kinetic energy of the projectile is imparted to the plate. Some of the energy is used to deform the plate, other energy is given off as light and heat and the reminder of the energy is imparted to the fragments as kinetic energy. Measuring or determining each of these energies is very difficult.

For penetration and perforation analysis, the only important aspect is to predict the kinetic energy (mass and velocity) of the fragments. Once this kinetic energy is determined, conservation of mass and energy, sometimes in terms of momentum, is applied to the projectile/target system. The analysis is still quite complex because the events that occur at projectile/target interface are somewhat unknown. Although many studies have been performed [2, 3], only highly controlled velocities, shapes, sizes and trajectories have been examined. As a result, numerous approximations and assumptions must be made in order to apply these analyses to fragments. Impact is much localized phenomenon. Stress and strain effects are usually limited to within 3-6 projectile diameters of the impact zone [4]. Impacted target materials may fail by a combination of several modes including spalling, plugging, petaling, ductile or brittle fracture and adiabatic shearing. Figure 1 shows some of these failure modes. In general these modes can be divided into regimes based on the ductility of the target [5].

Failure by spalling can occur on both sides front and back of the plate, and is characterized by formation of petals or ejects. In ductile failure, the impact impulse

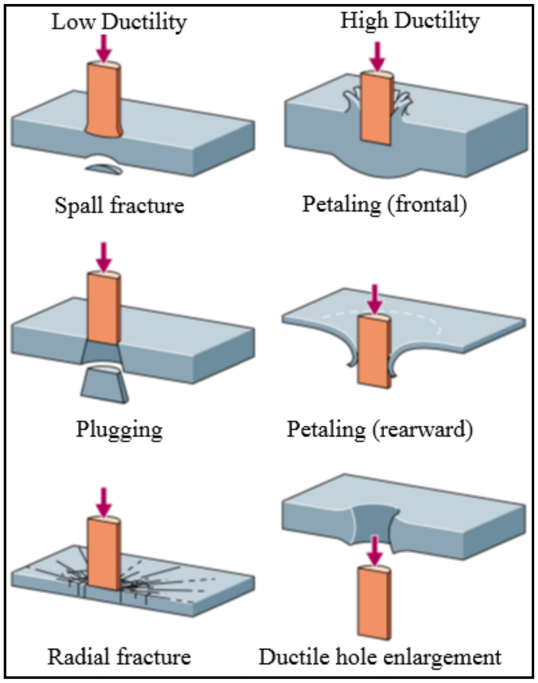

Fig. 1. Sketches of the penetration modes of monolithic plate. The modes are divided into two regimes based on the ductility of the target material [5]

overcomes the peripheral dynamic shear strength of the target material, pushing it onward and toward the impact surface to form a crater that is much larger than the projectile diameter. At the same time the projectile pushes into the target and there is hydrodynamic erosion and inversion of the projectile material against the proceeding face of the target.

The penetration process due to high-velocity impact can be represented by four phases: transient, primary penetration, secondary penetration and recovery. The first or transient phase is characterized by a very short pressure spike and occures when the projectile first contacts the target surface. The primary penetration phase is described as the period during which the projectile acts as a contributing force, imparting its kinetic energy to the target in a hydrodynamic manner. The secondary phase, sometimes reffered as cavitation, begins after the projectile is completely deformed and effctively removed from the system as a source of energy. It is marked by target deformation not caused directly by the kinetic energy of the projectile material. Instead the energy density behind the expanding shock wave continues to deform the target material. The fourth or recovery phase refers to the period during which the crater recovers or contracts slightly. Material just below the target surface anneals and recrystalizes.Projectile failure occures simultaneosly with target failure. Thus, penetration models involve both things. The projectiles deforms and flatten/spread out as they strike the target generating high resisting contact forces.

Penetration and failure in polymer matrix composites

Polymer matrix composites (PMCs) consist of a polymer resin reinforced with fibers i.e. fabrics and are highly anisotropic materials. PMCs respond to ballistic impact in ways that depend on their particular structure and thus are different from other protective materials. When a PMC is subjected to high-velocity impact, the kinetic energy is transferred from projectile to the PMC. The existence of two components, the fabric and the matrix, and their interface, makes the energy absorption mechanisms more complex than that of monolithic materials. For the complete understanding of the ballistic impact of PMCs different energy absorbing mechanism should be clearly understood. Possible energy absorbing mechanisms are: cone formation on the back face of the target, deformation of the orthogonal yarns of the fabric, fracture of primary yarns/fibers, delamination, matrix cracking, shear plugging and friction between the projectile and the target [6]. Also, the fabric architecture can influence the energy absorption mechanisms.

Cone formation on the back face of the target occurs during the ballistic impact event and can be explained on the basis of transverse wave propagation during ballistic impact. Figure 2 shows the scheme of cone formation in two-dimensional woven fabric composites during projectile impact. Here, d is the diameter of the projectile, r_{ti} is the surface radius of the cone and $z_i$is the distance traveled by the projectile. During the ballistic impact event, the distance traveled by the projectile and the depth of the cone are equal. The yarns that the bullet directly hits are called primary yarns.

These yarns resist penetration and undergo deformation due to the cone formation. The longitudinal compressive stress wave, generated upon impact, propagates outward along the yarn direction, forming a quasi-circular shape. The conical circular portion moves backward and stores kinetic energy by its motion.

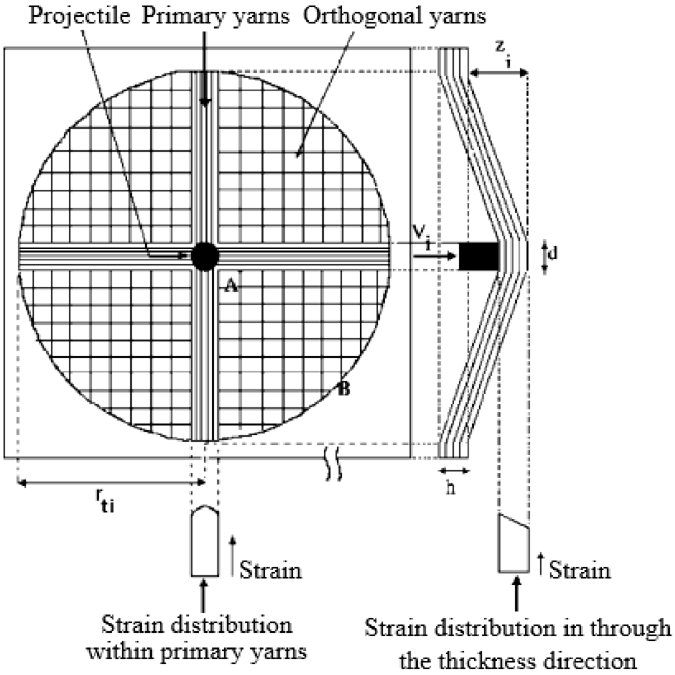

Fig. 2. Cone formation during ballistic impact on the back face of the composite target [6]

When PMC undergoes ballistic impact, the primery yarns deform and resist projectile penetration. The other yarns, called orthogonal yarns, also deform, but to a lesse extent due to the primary yarn deformation. This process stores kinetic energy. The highest overall strain is at the point of impact and it falls off along the radial direction. Once the strain is beyond the failure strain, sequential breakage of fibers will occur. This fiber breakage absorbs additional kinetic energy. The matrix has mechanical properties different from those of the yarns but it must carry the same deformation least delamination or slippage occur due to weak adhesion between the yarn and the matrix. There may be damage if the yarn strain is higher than the strain at failure in the matrix. As the material deforms, cracking and delamination will continue until total perforation occures. Energy absorption occurs through a combination of cracking and delamination [7-9]. After the yarns and the fabric fail, friction between damaged laminate and the projectile dissipates some of the kinetic energy from the projectile. Friction resistence depends on the shape of the projectile and increases with increasing composite thickness. Penetrating projectile forms a hole into the laminate which is larger than the projectile diameter. This aloso absorbs some of the kinetic energy of the projectile.

Conclusion

This brief survey of how materials undergo penetration shows that:
Penetration occurs by material failure at microstructural level. Failure in metals can occur by a combination of several modes including spalling, plugging, petaling, ductile or brittle fracture and adiabatic shearing. Failure in composites is more complex phenomenon. Possible energy absorbing mechanisms are: cone formation on the back face of the target, deformation of the orthogonal yarns of the fabric, fracture of primary yarns/fibers, delamination, matrix cracking, shear plugging and friction between the projectile and the target.

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