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Short Note

Impact of high velocity projectile to carbon-fiber fabric and alumina-fiber fabric

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Abstract—Carbon-fiber fabric(s) or alumina-fiber fabric(s) sandwiched between two 2-mm thick aluminum plates, are impacted by a high velocity projectile up to 2.7 km/s. The projectile penetrates into the specimen and results in a perforation hole. Based on the observations of the hole, the following is suggested. The interface affects the shape of the holes, a punch-out hole is generated in 10 sheets of the alumina-fiber fabrics, but no clear hole is made in 10 sheets of carbon-fiber fabrics.

Keywords: carbon-fiber fabric; alumina-fiber fabric; high velocity impact; damage; projectile.

1. INTRODUCTION

Advanced composites are becoming more important. Among them, especially, fiber reinforced metals (FRMs) show excellent heat- and environment-resistance, and have a high strength and modulus [1]. Therefore, they are promising as a structural material not only in aero- and space-engineering but also in energy technology, as in their use for engine parts for aircraft, turbine blades [2] and spacewalls. In this environment, impacts of foreign objects on such materials are inevitable. Studies on impact damage of FRPs have been started, but few studies on FRMs and on their reinforcing ceramic-fiber fabrics have been carried out until now. Data collection must first be performed.

In this study carbon-fiber fabric and alumina-fiber fabric are impacted by a high velocity projectile made of 6-6 nylon up to 2.7 km/s. The holes made in the specimens by the projectiles are investigated.

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2. EXPERIMENTAL PROCEDURE

2.1. Specimens

The carbon-fiber fabric used in this study was CO6341 (Toray Ind. Inc., 7 μm diameter fiber, 8-harness satin) and the alumina-fiber fabric was Altex SV-600-8H (Sumitomo Chemical Co. Ltd, 15 μm diameter fiber, 8-harness satin). The following treatment was carried out for maintaining the fabric-plane and preventing fabric-fraying, but not for making a FRM. The fabric was cut into 6-cm square forms, and then sandwiched between two 2-mm thick aluminum plates (Nilaco Co. Ltd, AL-013554). The number of fabrics put between each plate was 1 or 10. Hot press was performed in a H_2–Ar atmosphere at 630°C at 15 MPa for the case of aluminum/one sheet of carbon-fiber fabric/aluminum (CF/Al), aluminum/one sheet of alumina-fiber fabric/aluminum (AF/Al) and aluminum/aluminum (Al/Al). In the case of the specimens consisting of ten sheets of fabrics, the fabrics were stacked in parallel with the fiber direction and fixed with two aluminum plates. Hereafter, aluminum/ten sheets of alumina-fiber fabric/aluminum and aluminum/ten sheets of carbon-fiber fabric/aluminum are denoted as AF(10)/Al and CF(10)/Al, respectively. The characteristics of the raw materials are summarized in Table 1.

2.2. Impact tests

Impact tests were carried out using a two-stage light gas gun [3]. The projectile was 6-6 nylon, with an 8-mm diameter and 10-mm length, containing a 4-mm diameter Mn–Zn ferrite sphere in its center, which was used for velocity measurement by the so-called magnet-flyer method [4]. The details of the operation and the principle of the two-stage light gas gun are explained in [3] and [4].

The speciment was mounted in a holder fixed on the largest surfaces by two rings, whose inner diameter was 50 mm. It was held perpendicular to the direction of the projectile's travel.

A perforation hole was generated after the impact. The diameter of the hole was measured in three directions and their average represented the diameter. The surface where the projectile impacted is denoted as the front surface, and the surface that it came out is called the rear surface.

Table 1.
Characteristics of raw materials used in this study

	Density (g/cm^3)	Tensile strenght (MPa)	Young's modulus (GPa)
Aluminum (99.6%)	2.7	70	70.3
Alumina-fiber	3.3	1800	210
Carbon-fiber	1.75	3530	230

3. RESULTS AND DISCUSSION

Micrographs on a cutting surface of the Al/Al, AF/Al and CF/Al are shown in Fig. 1. In AF/Al and CF/Al, a gap exists between th two aluminum plates and individual fibers are also observed in it: no strong interaction occurs between fibers and aluminum plates in these cases. However, no clear interface region or gap is observed in Al/Al: two aluminum plates seem to become one thick plate.

The relationships between the diameter of the perforation holes on the front surface of the front plate in Al/Al, AF/Al and CF/Al, and the projectile's kinetic energy are shown in Fig. 2. The diameter increases with increasing kinetic energy in all cases.

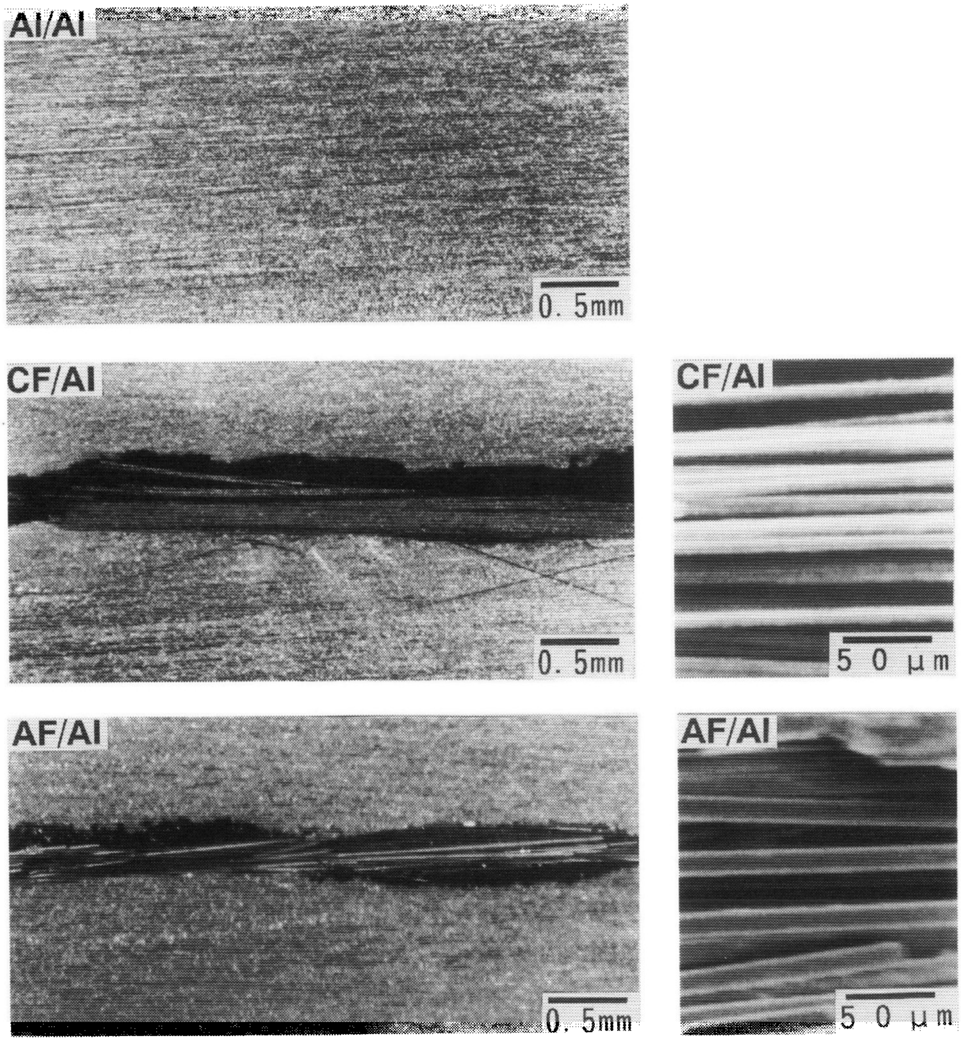

Figure 1. Micrographs on a cutting surface of the Al/Al, CF/Al, AF/Al specimens. Al/Al: aluminum/aluminum, AF/Al: aluminum/one sheet of alumina-fiber fabric/aluminum, CF/Al: aluminum/one sheet of carbon-fiber fabric/aluminum.

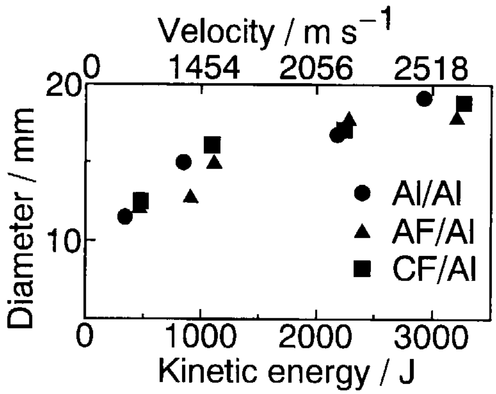

Figure 2. The diameter of perforation holes on front surfaces. Al/Al: aluminum/aluminum, AF/Al: aluminum/one sheet of alumina-fiber fabric/aluminum, CF/Al: aluminum/one sheet of carbon-fiber fabric/aluminum.

However, no significant difference can be observed in the three at the same energy. In all cases, hole diameters are larger than the projectile's diameter. These phenomena can be explained as folows; a projectile shows plastic flow due to the pressure at impact and the diameter becomes larger than that of the initial value, becoming three times in one case [5]. The exact pressure caused by the impact cannot be calculated, because no Hugoniot data exist for the materials used in this study. From an estimation using Hugoniot data [6] of similar materials in this study (aluminum, carbon, alumina and nylon) by the one-dimensional impedance matching method, the pressure initiated in aluminum by the impact of nylon is as high as 3 GPa to 12 GPa in this velocity region. This value justifies the previous explanation.

Figure 3 shows the hole diameter on the rear surface of the rear plates and the kinetic energy of the projectiles. The difference among Al/Al, AF/Al and CF/Al is first discussed. In all cases the diameter also increases with increasing kinetic energy. In AF/Al and CF/Al, the hole diameter in the rear plates is larger than that in the front plates, while in Al/Al the hole diameter is the same as that in the front plates. This may be caused by the difference in the interface between the two aluminum plates. The interface of Al/Al is strongly bonded by the hot-press but no bonding, or weak bonding, occurs in AF/Al and CF/Al, because a fabric sheet is inserted between them as can be seen in Fig. 1. The rear aluminum plates in AF/Al and CF/Al are then largely deformed by the projectile movement; therefore, they show a bigger hole in the rear plates. This indicates that interface bonding must play an important role in deformation and its fracture (damage) behavior in materials having interfaces: i.e. in FRMs.

Figure 3 also shows the relationships in CF(10)/Al and AF(10)/Al. CF(10)/Al shows smaller holes than that of the projectile's diameter but AF(10)/Al shows much bigger holes. The hole diameters in the front plates of both AF(10)/Al and CF(10)/Al are similar to those in the specimen with one fabric sheet. The difference surely arises from the difference in the number of sheets.

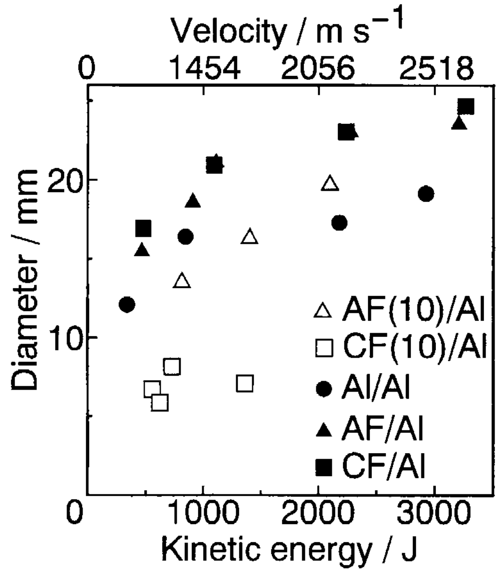

Figure 3. The diameter of perforation holes on rear surfaces. Al/Al: aluminum/aluminum, AF/Al: aluminum/one sheet of alumina-fiber fabric/aluminum, CF/Al: aluminum/one sheet of carbon-fiber fabric/aluminum, AF(10)/Al: aluminum/ten sheets of alumina-fiber fabric/aluminum, CF(10)/Al: aluminum/ten sfeets of carbon-fiber fabric/aluminum.

Photographs of fabrics at the rear side and rear aluminum plates in AF(10)/Al and in CF(10)/Al are show in Fig. 4 for a kinetic energy of around 1400 J. No visible holes are observed in the carbon-fiber fabrics. A large hole, on the contrary, is generated in the alumina-fiber fabrics. The rear aluminum plate in CF(10)/Al shows a small deformation and a small hole, while the rear plate results in a larger hole and a larger deformation in AF(10)/Al, which is evidence that a larger stress is applied to the plate in AF(10)/Al than in CF(10)/Al. The kinetic energy of the projectile impacted at the rear plate might be smaller in CF(10)/Al than that in AF(10)/Al, i.e. ten sheets of carbon-fiber fabric reduces the kinetic energy more than ten sheets of alumina-fiber fabric. From the Hugoniot data, the stress at impact in the alumina-fiber fabric is more than three times larger than that in the carbon-fiber fabric, and more than twice that in aluminum [6]. However, the hole diameter in the rear plate in AF/Al is similar to that in CF/Al and larger than that in Al/Al. Therefore, the size of the diameter in the rear plate cannot be explained only by the stress initiated at the impact.

Other factors should be considered. Areal density (weight along the whole thickness per unit area) or material density affects the absorption of the kinetic energy [7]. The density of alumina-fibers is larger than that of carbon fibers as shown in Table 1. Moreover, the diameter of alumina-fibers is more than twice that of carbon fibers: AF(10) is then thicker than CF(10). Both areal and material densities of AF(10)/Al are higher than those of CF(10)/Al. Therefore, we cannot give any suitable explanation for absorption of the projectile's kinetic energy based only on areal and material densities.

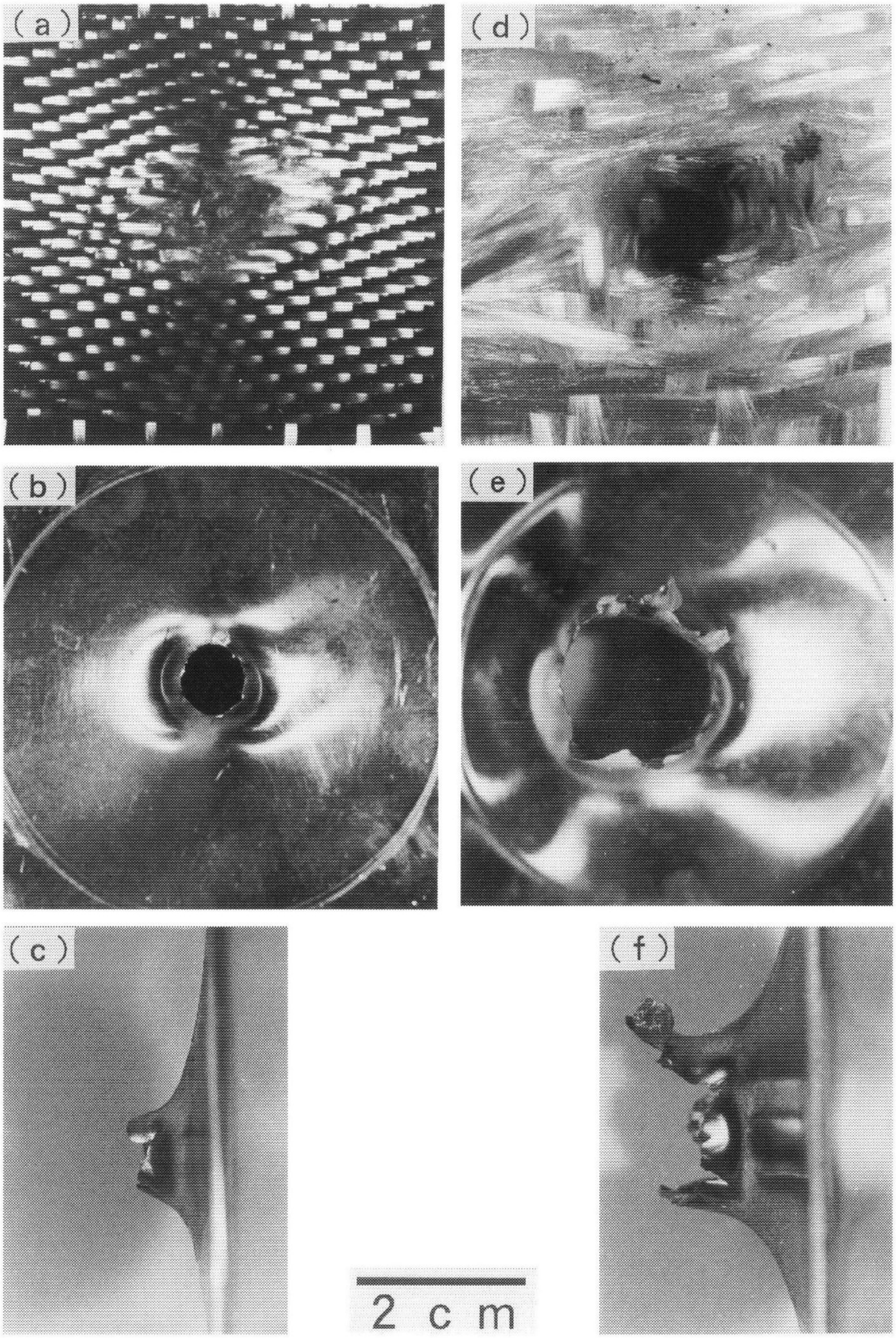

Figure 4. Photographs of fabrics at rear side and the rear-side aluminum plates in CF(10)/Al (a, b, c) and AF(10)/Al (d, e, f) at the kinetic energy of about 1400 J. (a) carbon-fiber fabric, (b) aluminum plate in bottom view, (c) aluminum plate in side view, (d) alumina-fiber fabric, (e) aluminum plate in bottom view, (f) aluminum plate in side view.

The above discussion allows us to postulate the following explanation. The difference in the hole diameter in the rear plate must be caused by the difference between the characteristics of the carbon fibers and alumina fibers, because the woven pattern is similar in both fabrics. The factors that affect impact damage in ceramics are usually fracture toughness, hardness and strength [8]. The fracture toughness of a carbon fiber is reported as 2 $\mathrm{MPa\,m^{1/2}}$ [9]. The toughness of alumina fibers is not clear, but that of polycrystalline alumina is around 4 $\mathrm{MPa\,m^{1/2}}$ [10] which is larger than that for carbon fibers. The hardness of alumina fiber should be higher when compared to carbon fibers. However, the strenght of alumina fibers is half that for carbon fibers and Young's modulus is nearly the same (Table 1). Therefore, the strain to failure of the alumina fibers is half that of the carbon fibers. In AF(10)/Al, a punch-out hole is made, as can be seen in Fig. 4. Such a hole must be caused by the smaller strain to failure of aluminum fibers. Strain to failure of reinforcement fibers, or fabrics, must be significant for impact damage investigation, but details still remain to be solved.

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