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Effect of unidirectional prepreg size on punching of pseudo-ductile CFRP laminates and CFRP/metal hybrid composites

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ABSTRACT

Punching is an efficient and economical process for producing a hole in structures for functional requirements, repair, maintenance, and so forth. Toward extending the use of punching to new materials, the punching of multilayer CFRP laminates and CFRP/metal hybrid composites was investigated. In this paper, the effect of the unidirectional (UD) prepreg size on the shear behavior of pseudo-ductile CFRP laminates and CFRP/metal hybrid composites is discussed on the basis of experimental observations. CFRP laminates were individually fabricated using standard (149 g/m^2) and thin-ply (62 g/m^2) prepregs, and were bonded with three metals (aluminum alloy A6061, magnesium alloy AZ31, and advanced high-strength steel SPFC980) by utilizing an autoclave (co-curing) and adhesive glue for hybrid composite application, then punched by a circular die and punch tool at room temperature. The effects of the UD prepreg size on the punch force, punching resistance *(Ks)*, quality, and sheared surfaces of the through-holes are discussed. The shear behavior for punching in different composites was also studied by microscopic examination. Our results are expected to enable quantitative design for the development of punched CFRP laminates and CFRP/metal hybrid composites.

1. Introduction

Carbon fiber structural components increase the suppleness of in the key structures of automotive body parts, sometimes complementing a metal and sometimes acting as independent structural members. Intelligent interplay between carbon-fiber-reinforced plastic (CFRP), aluminum, and steel tunnels can be found in A, B, and C pillars, as well as in much of the roof, which are all built using CFRP/metal hybrid parts to reinforce the body [1]. CFRP and CFRP/metal hybrid structures have been used in several cases, and carbon/epoxy, glass/epoxy, and hybrid composites have been used in the reinforcement of structures [2]. The CFRP/metal hybrid composites were produced by stacking CFRP on a metal plate to enhance the specific mechanical properties relative to those of automotive structures [3,4]. For functional requirements, and for the repair and maintenance of mechanical parts, there is expected to be a growing need in the near future for automotive parts with a pass-through hole in CFRP panels, and CFRP/metal hybrid components. Accordingly, a study on how to produce circular and square holes in CFRP and CFRP/metal hybrid composites by a punching process is necessary.

More specifically, the study of shear behavior can increase understanding of all punching processes for plastic and hybrid composites. One of the most important aspects of a punched surface is its quality. According to the investigation of the blanking of fiber-reinforced plastics, composite laminates with various types of fibers and polymeric matrices can be blanked with sharp edges by precise vibro-punching [5]. To obtain a significant through-hole by a piercing process in the actual production of a novel material such as a CFRP laminate, many technical issues should be examined and resolved. In a previous study, a thin CFRP laminate was pierced while varying conditions such as the clearance and the shape of the punch. The effect of the tool clearance and punch shape on the damage in the specimen was studied to optimize the punching process [6]. Also, mechanical conditions such as the tool clearance and the punch velocity in the shearing test were varied to determine the characteristics of unstable cutting of a 0.5-mm-thick polycarbonate (PC) specimen subjected to straight punch/die shearing [8]. Undoubtedly, previous research on the punching of metals, including aluminum alloy, magnesium alloy, and advanced high-strength steel, has provided much information on punch-shearing to clarify the effect of tool parameters and improve the quality of sheared edges by tool design [9–13]. Furthermore, to obtain the material behavior during the punching process, it is more reliable to use the finite element method (FEM), analytical modeling, and experimental tests in combination than only an empirical approach [14]. Similarly, the use of a numerical simulation in conjunction with a punch-shear test on plastic materials has been presented. The effect of the punch and specimen

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dimensions on the punch behavior of S-2 glass/SC15 resin composites and the evolution of damage has been studied [15,16]. Moreover, quasi-static punch-shear tests were employed to clarify the damage that can evolve during penetrating impact. The FEM was executed using the ABAQUS/Explicit code with a progressive damage model to simulate experiments [17].

In addition, not only the tool geometry but also the properties of the material affect the sheared hole in the punching process. Here the fiber orientation relative to the cutting line of the cutting force as an example. An experimental study on the blanking of unidirectional (UD) CFRP at different fiber orientations to the cutting line was performed. It was shown that the cutting force decreases from the perpendicular orientation to the parallel fiber orientation to the cutting line [18]. Also, to better comprehend the cutting mechanisms of processes involving but not limited to an in-plane cutting force, the behavior of UD glass/epoxy composites under an out-of-plane cutting force was examined. Eight different fiber orientation sets with respect to the direction of the cutting force were examined in a previous study [19].

Different from the punching of a single layer, microholes were formed on a laminate that consisted of low-temperature co-fired ceramic and polyethylene terephthalate (PET) layers to study the correlation between the quality of punched holes and process conditions such as specimen thickness and tool size [20]. Furthermore, to extend the punching process to brand-new materials, the blanking of fiberglass/polyvinyl chloride (PVC) thermoplastic laminates and composite/aluminum hybrid composites was studied at room temperature and elevated temperature. The blanked laminates and hybrid composites had sheared edges with high quality only at room temperature [21]. Also, a sandwich structure comprising two metal sheets outside and a plastic core for lightweight design to enhance the capacity of loading has been fabricated. Conventional punching strategies and empirical techniques may not be applicable to this hybrid composite. The punch-shear process was examined by FEM to predict the required force and the sheared surface geometry for the hybrid composite [22], providing useful knowledge for the punching of plastic/metal hybrid composites.

The investigation of mechanical properties such as yield and ultimate tensile strength (UTS) from punch-shear experiments is also meaningful when the available material is limited or novel at the initial stage of product development. The punch force was found to depend almost linearly on the thickness and yield stress of the thermoplastic foil, which allows the easy evaluation of the tool forces for targets [23]. The punch-shear curves were also estimated from the linear correlation between the shear strength and tensile strength [27].

According to the above, the application of lightweight hybrid structures to transportation is expected to gradually increase. However, there are no reports on the punching of through-holes in pseudo-ductile CFRP laminates and CFRP/metal hybrid composites for functional use. Therefore, the aim of this work is to carry out a series of experiments on the punching process by adopting various laminated materials and punch-shear sequence plans. The key objectives of the present investigation are to examine the punch-shearing of a through-hole in laminated composites through a force analysis, with special focus on the effect of decreasing the prepreg thickness from the standard value as well as the effects of the punch speed, specimen thickness, and type of lamination on behavior including punching resistance, the shear mechanism, and punched-hole quality in laminated composites.

2. Experimental procedure

2.1. Materials

CFRP laminates with thin-ply pre-impregnated sheets are considered to exhibit superior damage resistance to the standard type [28]. In this work, multilayer CFRP laminates and CFRP/metal hybrid composites were used to study the punching process with different UD CFRP prepreg thicknesses. As shown in Table 1, the material systems used in this study were standard (0.1-mm-thick) and thin-ply (0.04-mm-thick) UD carbon/epoxy pre-impregnated sheets fabricated by the hand lay-up process. The standard sheets were P3252S-10 sheets with T-700SC carbon fibers from TORAYCA, Japan. Thin-ply Mitsubishi Rayon TR50S carbon fiber/Bisphenol A prepreg sheets were supplied by the Industrial Technology Center of Fukui Prefecture, Japan. The nominal volume fraction of the carbon fibers and the filament diameter for both pre-impregnated sheets were 58% and 7 µm, respectively. Moreover, the cleaned aluminum alloy A6061 (surface roughness of Ra: 0.26 µm), magnesium alloy AZ31 (surface roughness of Ra: 0.22 µm), and advanced high-strength steel SPFC980 (surface roughness of Ra: 0.80 µm) sheets with a thickness of 1.0 mm were used to produce hybrid composites with the CFRP laminate.

Table 1
Characteristics of UD CFRP prepreg sheets.

Size	Prepreg thickness (mm)	Carbon fiber[a]	Epoxy[b]
Standard	0.1	T-700SC	P3252S-10
Thin-ply	0.04	TR50S	Bisphenol A

[a] The strength, filament diameter, and volume fraction of the carbon fibers are equivalent for both types.
[b] The glass transition temperature (T_g) is around 110 °C for both types, as measured by differential scanning calorimetry (DSC) and provided from the vendors.

2.2. Fabrication of CFRP laminates and CFRP/metal hybrid composites

Fig. 1a schematically shows the stacking of CFRP pre-impregnated sheets and the hand lay-up of prepregs on the metal. To produce the multilayer cross-ply CFRP laminates, several layers of UD carbon/epoxy prepregs with $[0/90/0]_{NS}$ (NS stands for the number of symmetrical layers) fabricated by the hand lay-up process were cured in an autoclave under an applied pressure of 0.5 MPa and a temperature of 130 °C as shown in Fig. 1b, where the temperature was increased from room temperature close to T_g at a rate of 2 °C/min. This temperature was maintained for 30 min to ensure that the thermosetting resin changed from the glassy state to a more balanced rubberlike state. Then the sample was further heated to the curing temperature with the same rate of temperature increase, at which it was cured for 2 h. Finally, it was cooled to room temperature to obtain cured laminated carbon fiber/epoxy resin sheets as shown in Fig. 1c. The nominal thickness of the fabricated standard $[0/90/0]_{3S}$ and thin-ply $[0/90/0]_{8S}$ laminates was 2.0 mm, which are denoted as "THICK" in the following. Also, the nominal thickness of the standard $[0/90/0]_{1S}$ and thin-ply $[0/90/0]_{2S}$ laminates was 0.6 mm, which are denoted as "THIN" in the following. Both THICK and THIN specimens with standard and thin-ply laminates were prepared in this study. Furthermore, the nominal thickness of the bonded CFRP/metal hybrid composites was 3.0 mm, where a THICK $[0/90/0]_{NS}$ CFRP laminate and a metal layer were joined with each other by two approaches, autoclave co-curing [29] and bonding with a glue adhesive (DEVCON PW I), as also shown in Fig. 1c.

2.3. Punching processes

The clearance between punch and die is the critical contribution to the punching process. Most punching tool is used to form the through-hole in metals that have a crystalline structure with precise angle of a weakness fracture plane, as well as it induces and connects fractures in upper and lower surfaces of the material by a suitable clearance. Accordingly, the optimization of 0.1 mm punch die clearance and punch shape depends on damage was studied for the piercing of CFRP $[0/90]_S$ laminates [6]. Also, according to the damage produced on the sheared region of punched hole in GFRP laminate by punching process with 0.1 mm punch die clearance, is limited and comparable to that