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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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A R T I C L E I N F O

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A B S T R A C T

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

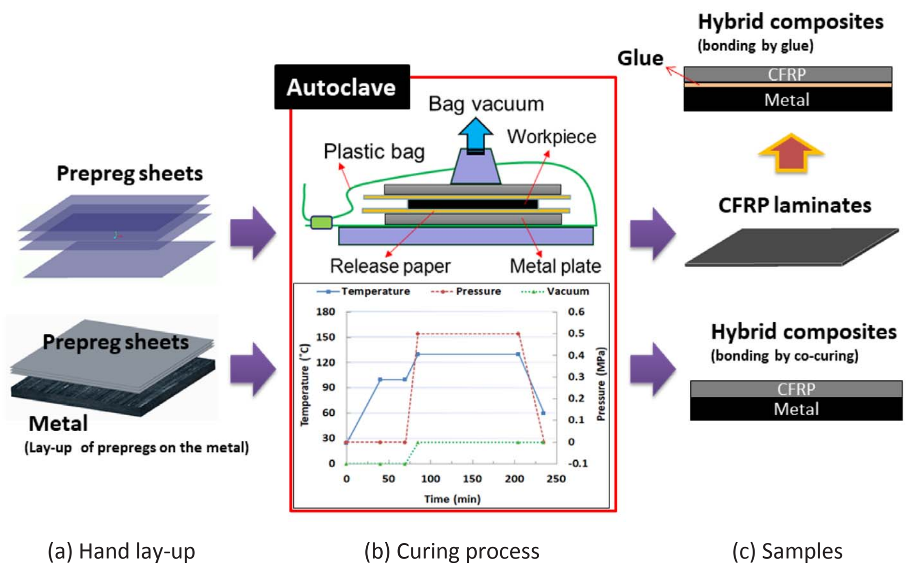


Fig. 1. Fabrication flow process of workpieces.

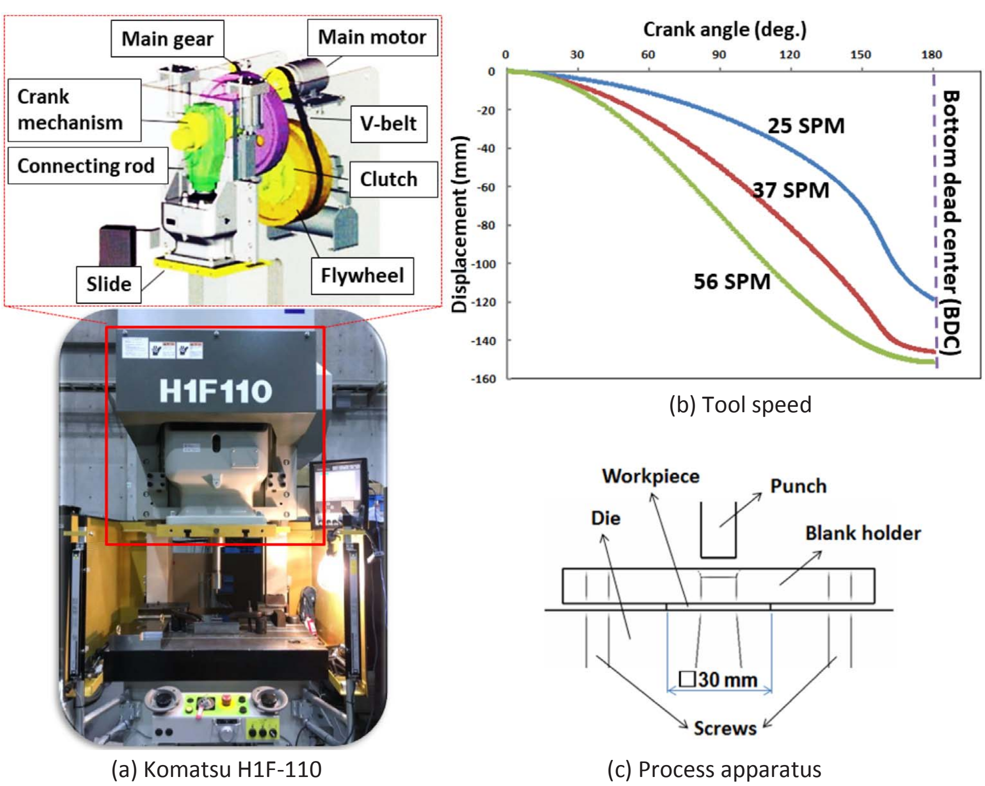


Fig. 2. Servo press machine and punching die set.

produced by drilling process [7]. In this study, on the punching of novel composites, a die with a circular hole of 10.2 mm diameter and a punch with a 10.0 mm diameter, giving a fixed 0.1 mm clearance, were manufactured for our experiment as shown in Fig. 2c. A blank holder with two screws was applied to exert a blank holder force on the workpiece. The punch and die were made of SKD11 tool steel for cold work. The entire punching die was installed on a Komatsu H1F-110 hybrid AC servo press (see Fig. 2a) to cut a through-hole in the specimens at room temperature, and the punch of the piercing apparatus was pushed downward by a servo actuator. Punch tool was fixed on the slide (slide was driven down and up by crank link mechanism; crank angle 0° ~ 180°: slide down, and crank angle 180° ~ 360°: slide up). The slide was driven down with different speed for punching a through-hole in the composites, and then driven up (back to the original point) with full speed after punching a through-hole.

The load and displacement were recorded during the loading process. Load-displacement curves were recorded as well as the output from a computer to compare the punch force, punching resistance (*Ks*), and so forth. The punch load-displacement curve is meaningful in the punch-shear process and indicates the properties of the materials. The maximum punch load is a major factor at the design stage of the punching process, especially in the selection of the press machine. The work done by the load in the punching process and the punching resistance (*Ks*) can be calculated from the maximum punch force as follows [23]:

$$Ks = F_{max}/\pi \cdot D_{avg} \cdot t_0 \tag{1}$$

where *Ks* is the punching resistance, F_{max} is the maximum punch load,

D_{avg} is the average of the diameters of the punch and die, and t_0 is the nominal thickness of the workpiece.

To begin with, three punch speeds were investigated, and the variation of 9, 37, and 56 strokes per minute (SPM), is shown in Fig. 2b. The effect of the prepreg size on the punching of the standard laminate and thin-ply laminate is discussed for THICK and THIN specimens with various tool speeds. In the second stage, the standard laminate and thin-ply laminate were sandwiched by dummy metallic sheets during punch tests. The dummy sheets, which sandwiched the CFRP laminate, were discarded after punching. The dummy metallic sheets, including two types of aluminum alloy A5052 (t0.8 mm) and stainless steel SUS304 (t0.5 mm), act as protective materials and a large increase in the hole quality was expected. Finally, for use in advanced applications, CFRP/metal hybrid structures and their bonding techniques including autoclave co-curing and glue bonding, which are important factors that may affect the shear behavior, were studied by punching CFRP/metal hybrid composites. Thus, these basic punching experiments are also able to assistant the development of bolted joints in local analysis for the laminates and sandwich structures are widely used in aerospace industries. The bolted joints in parts assemblies lead to a failure phenomenon called pull-through was studied with the discrete ply model in thin laminates [24], and non-linear finite element analysis in sandwich composites [25]. On the other hand, the key parameters such as fiber cutting, delamination and diffuse damage in the laminate for self-piercing riveted joints [26] also could be approached by the basic punching test.

In this study, the maximum punch force and punching resistance (*Ks*) of the samples were calculated then the effect of the prepreg thickness on them was investigated. The experiments were designed to examine the effect of the above mentioned parameters where two to three samples were used per condition on the punching of CFRP laminates and CFRP/metal hybrid composites, Table 2 shows the design of the experiments and the 0.1 mm constant clearance with different thicknesses of workpiece corresponding to Table 3 were chosen.

3. Results and discussion

3.1. Punching behavior for various punching speeds and specimen thicknesses

Generally, stress relaxation occurs in polymers under a strained state for a period of time. The punch-shear velocity appears to affect the shearing characteristics of polymer materials. Also, a few studies [8,23] have considered the effects of punch speed on the shearing process of a polymer workpiece. Accordingly, multilayer CFRP standard and thin-ply laminate worksheets, which had nominal specimen thicknesses of 2.0 mm (THICK) and 0.6 mm (THIN), were subjected to punching with servo press speeds of 9, 37, and 56 SPM. Fig. 3 shows the characteristics of the maximum punch load on THICK/THIN standard laminates and THICK/THIN thin-ply laminates with respect to the machine speed. The reference maximum punch loads tended to decrease with increasing machine speed; these relations were approximately linearly by Eqs. (2–5) as also shown in Fig. 3. This outcome can be simply explained by the fact that a low punching velocity provides sufficient time to increase the force compressing the skin layers. In contrast, at higher punching speeds, the material shear strength cannot resist the external punch-shear for a short time and shearing directly occurs. With increasing punching speed, the maximum punch load for both the standard and thin-ply laminates decrease in the THICK and THIN specimens. These relationships were approximated and expressed by the following equations:

$$F = -0.059\ V + 24.812 \tag{2}$$

$$F = -0.0261\ V + 17.828 \tag{3}$$

$$F = -0.0439\ V + 10.672 \tag{4}$$

$$F = -0.0344\ V + 7.3361 \tag{5}$$

Comparing the punch loads obtained in the experiments, the THICK thin-ply laminate exhibits an approximately 25% lower maximum punch load than the THICK standard laminate. Also, the THIN thin-ply laminate exhibits an almost 35% lower maximum punch load than the THIN laminate made with standard prepregs. On the other hand, the maximum punch load is 160% increase when the thickness of specimen changing from THIN standard laminate to THICK standard laminate. Also, the maximum punch load in THICK thin-ply laminate is 200% increase relatively to the THIN thin-ply laminate. Consequently, the punching of a laminate made with the standard prepreg sheet results in a larger punch force than that for the thin-ply laminate. It can be inferred that higher punch load is necessary acting cut on a unit, which is fabricated with thicker prepreg. That is, decreasing the prepreg thickness from 0.1 to 0.04 mm enables a lower cutting force as well as a significant decrease in the punching resistance.

Table 2
Design of experiments on punching processes.

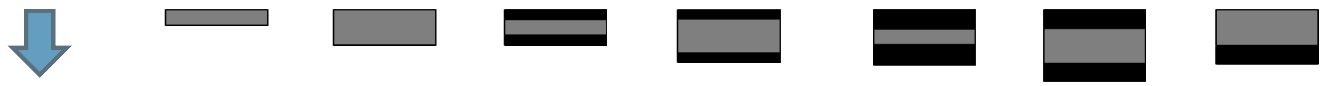
Specimen type	SPM (mm/min)	Dummy sheet	Bonding method
CFRP laminates			
THICK standard	56, 37, 9	N/A, A5052 (t0.8 mm), SUS304 (t0.5 mm)	—
THIN standard	56, 37, 9	N/A, A5052 (t0.8 mm), SUS304 (t0.5 mm)	—
THICK thin-ply	56, 37, 9	N/A, A5052 (t0.8 mm), SUS304 (t0.5 mm)	—
THIN thin-ply	56, 37, 9	N/A, A5052 (t0.8 mm), SUS304 (t0.5 mm)	—
CFRP/metal hybrid composites			
THICK standard/A6061	37	N/A	Co-curing, Glue
THICK standard/AZ31	37	N/A	Co-curing, Glue
THICK standard/SPFC980	37	N/A	Co-curing, Glue
THICK thin-ply/A6061	37	N/A	Co-curing, Glue
THICK thin-ply/AZ31	37	N/A	Co-curing, Glue
THICK thin-ply/SPFC980	37	N/A	Co-curing, Glue

3.2. Characteristics of multilayer CFRP laminates

Additionally, the carbon/epoxy composite laminates were fully punched under displacement control. A metal-like force-displacement curve was obtained from the confined punch testing. The punching curves of the studied THICK CFRP laminates obtained from the standard and thin-ply laminates are shown in Fig. 4. As illustrated in Fig. 4a, the force displacement curve can be separated into three main steps. The first step is dominated by compression of the CFRP laminate (load accumulated). In the second step, the shearing of the skin sheets occurs. When the skin sheets are cut (load peak), shearing begins and the core material is sheared. In the final step, the force is dominated by the friction between the different layers of the punch. Comparing both cases, the multilayer CFRP laminate exhibits shear behavior with about a 20–30% smaller load peak when the pre-impregnated sheets are scaled down to 0.04 mm from the standard value.

Microsections of the cutting surfaces are shown in Fig. 4b. To obtain an overall view of the composite specimens, the half-punch steps show two different displacement levels for each CFRP laminate. The first half-punch (displacement ≈ 25% of specimen thickness) causes the roll-over of the skin layers while the laminate is compressed by the punch and shear bands are formed. Furthermore, the blanked part of the THICK standard laminate exhibited clear delamination than the THICK thin-ply laminate for a half-punch with displacement equal to about

Table 3
Methodology and punching clearance of experiments.

Materials Punching direction	THIN CFRP laminate	THICK CFRP laminate	THIN CFRP W/ SUS304	THICK CFRP W/ SUS304	THIN CFRP W/ A5052	THICK CFRP W/ A5052	THICK CFRP/metal
							
Total thickness (t_0)	0.6 mm	2.0 mm	1.6 mm	3.0 mm	2.2 mm	3.6 mm	3.0 mm
Absolute clearance	Relative clearance (= absolute clearance/t_0)						
0.1 mm	16.7%	5%	6.25%	3.3%	4.5%	2.8%	3.3%

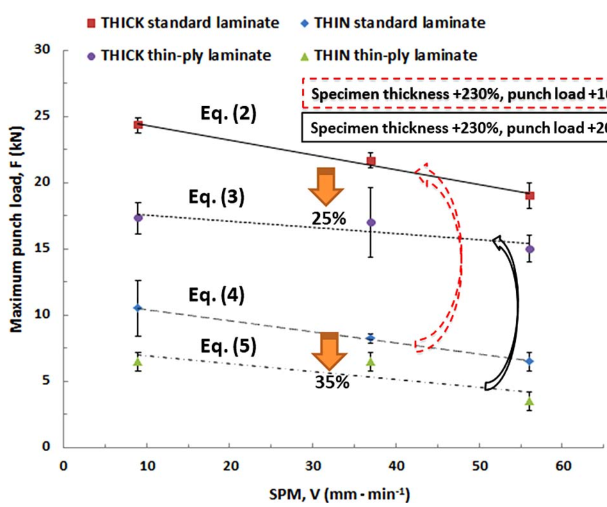
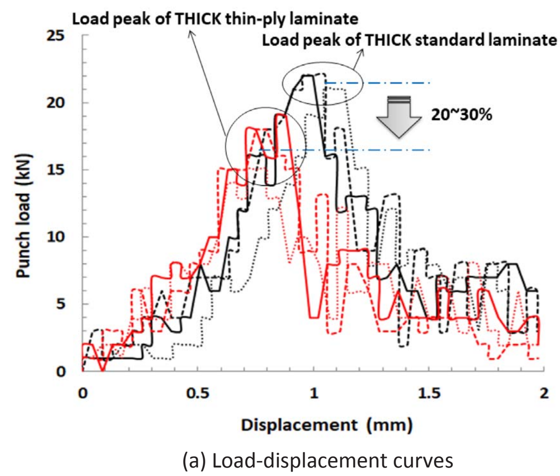


Fig. 3. Relationships between punching load and machine speed for CFRP laminates.

60% of the specimen thickness. A previous study [28] has shown that the growth of damage is considerably different between standard and thin-ply laminates. The accumulation and growth of delamination and matrix cracks occurred in the standard laminates, while sudden fiber fractures occurred in the thin-ply laminates. It is considered that the thin-ply laminate has high resistance against matrix cracking and delamination near the skin, and thus fiber failures suddenly occurred. In the same way, the fibers suddenly break as well as peel off the matrix from near the back face of the sheared through-hole in the thin-ply laminate as shown in the final image of Fig. 4b. In contrast, for the standard laminate slight burrs exist on the back face of the punched through-hole.

Furthermore, the concept of punching resistance (*Ks*) is related to the yield stress measured in tensile tests, where the maximum punch force is also related to the initial cross section of the specimen. It was found [23,27] that the resistance in punching is a material property that depends slightly on the thickness of the workpiece. The shear cutting forces were found to depend almost linearly on the foil thickness and the yield stress of the foil material, which allows simple initial estimates of the punching forces for dimensioning purposes. It follows that the *Ks*, which is known to satisfy $F_{max} = Ks \cdot \pi \cdot D_{avg} \cdot t_0$, is correlated with the yield stress (σ_y) and ultimate tensile strength (σ_{UTS}) in tensile testing.

Furthermore, the nominal stress-strain curves of the THICK standard and THICK thin-ply laminates comprising the pseudo-ductile carbon/epoxy sheets at room temperature were obtained in accordance with ASTM D3039 (dimensions of tensile specimen: L250 mm × W25 mm × t2.0 mm) as shown in Fig. 5. These nominal stress-strain responses of pseudo-ductility in CFRP laminates by giving the definition of mechanical properties such as ultimate tensile strength (σ_{UTS}), yield stress (σ_y), etc. [30]. Hence, not only is it found by the Eqs. (6) and (7) that the standard $[0/90/0]_{3S}$ laminate has a significant UTS



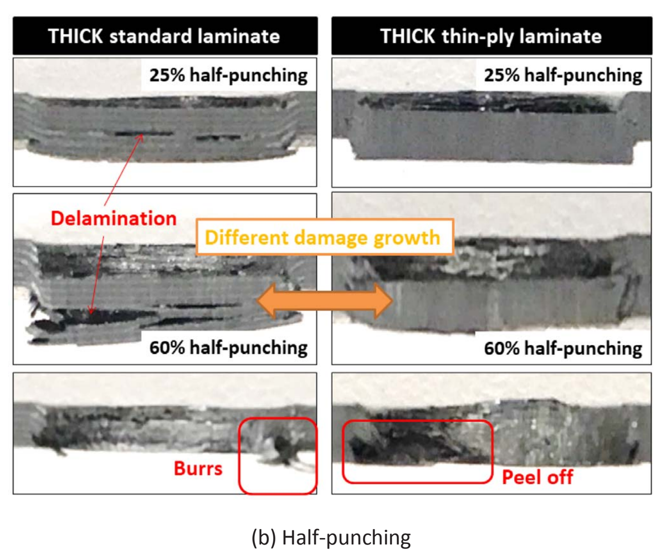


Fig. 4. Comparison of responses of THICK standard and thin-ply laminates.

of 1482 MPa and a yield stress of 280 MPa but it is also found that the UTS was 1356 MPa and the yield stress was around 750 MPa for the thin-ply $[0/90/0]_{8S}$ laminate. These relationships were approximated and expressed by the following equations:

$$\sigma = -4E7\varepsilon^6 + 5E7\varepsilon^5 - 2E7\varepsilon^4 + 5E6\varepsilon^3 - 651111\varepsilon^2 + 38816\varepsilon - 108.4 \quad (6)$$

$$\sigma = -5E7\varepsilon^6 + 5E7\varepsilon^5 - 2E7\varepsilon^4 + 4E6\varepsilon^3 - 339292\varepsilon^2 + 15849\varepsilon + 53.559 \quad (7)$$

Fig. 6 shows a strong correlation between *Ks*, ultimate tensile strength (σ_{UTS}), and yield stress (σ_y) for multilayer CFRP laminates. One

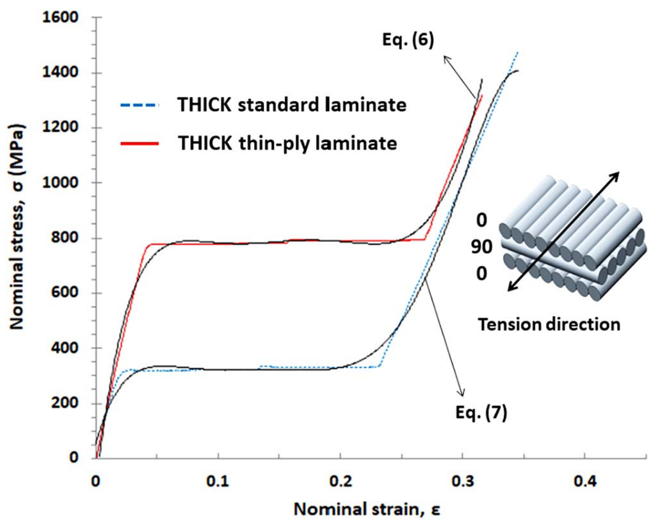


Fig. 5. Stress-strain curves of pseudo-ductile CFRP laminates at room temperature.

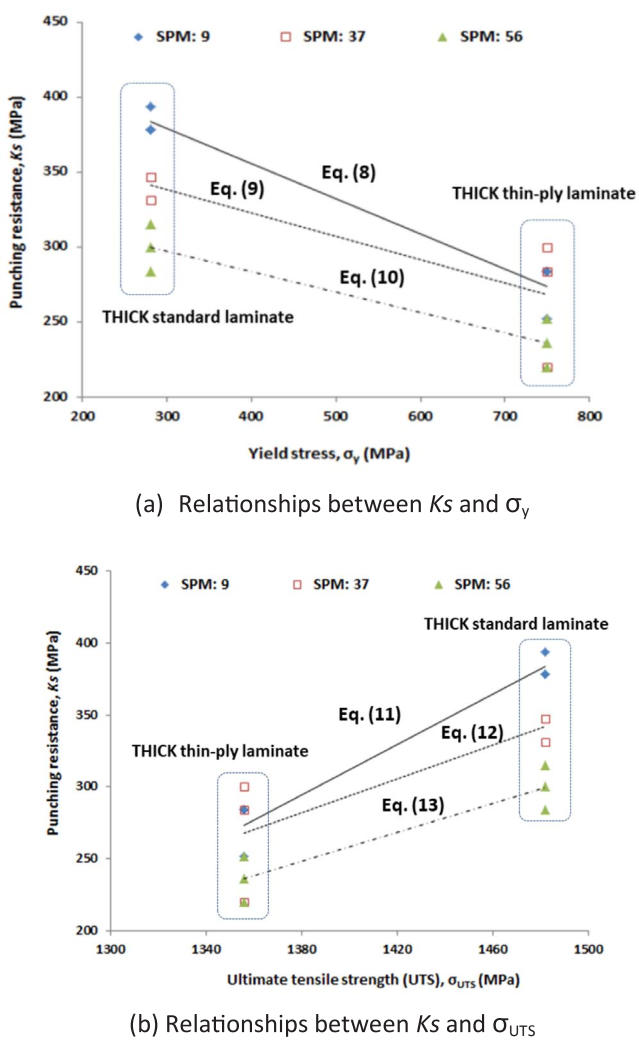


Fig. 6. Relationships between punching resistance and nominal stress.

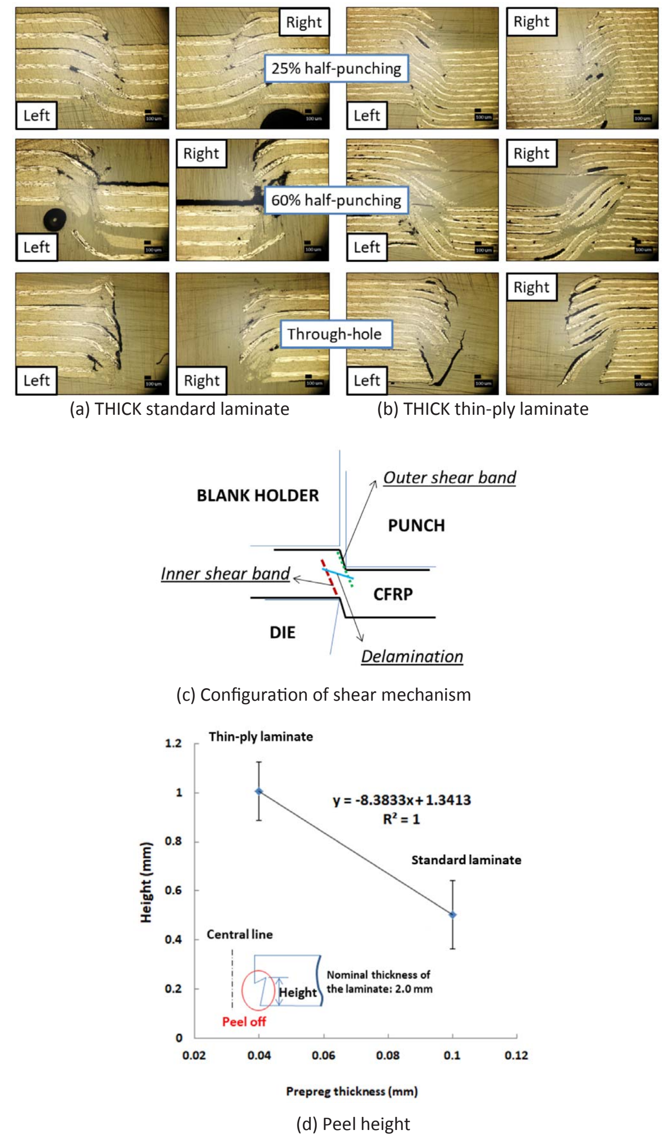


Fig. 7. Side-view photographs on shearing of the CFRP laminates.

set of experiment data can be well fitted by the linear functions $Ks = -0.16\sigma_y + 386$ and $Ks = 0.59\sigma_{UTS}$-525 for multilayer CFRP laminates punched at a tool speed of 37 SPM. Accordingly, the standard laminate with a higher UTS exhibits a higher punching resistance than the thin-ply laminate. Likewise, the thin-ply laminate exhibits superior yield strength despite its inferior punching resistance to the standard laminate. Hence, the punch-shear forces were found to depend highly linearly on the tensile strength and yield stress for the CFRP laminates made with different prepreg sizes by the Eqs. (8–13), which allows simple initial estimates of the punching forces for dimensioning purposes. These relationships were approximated and expressed by the following equations:

$$Ks = -0.234\sigma_y + 448.87 \quad \text{(SPM: 9)} \tag{8}$$

$$Ks = -0.1567\sigma_y + 385.55 \quad \text{(SPM: 37)} \tag{9}$$

$$Ks = -0.1355\sigma_y + 337.6 \quad \text{(SPM: 56)} \tag{10}$$

$$Ks = 0.873\sigma_{UTS} - 910.48 \quad \text{(SPM: 9)} \tag{11}$$

$$Ks = 0.5847\sigma_{UTS} - 524.79 \quad \text{(SPM: 37)} \tag{12}$$

$$Ks = 0.5053\sigma_{UTS} - 449.17 \quad \text{(SPM: 56)} \tag{13}$$

3.3. Shear behavior of multilayer CFRP laminates

The punching process has often been used to produce a hole for

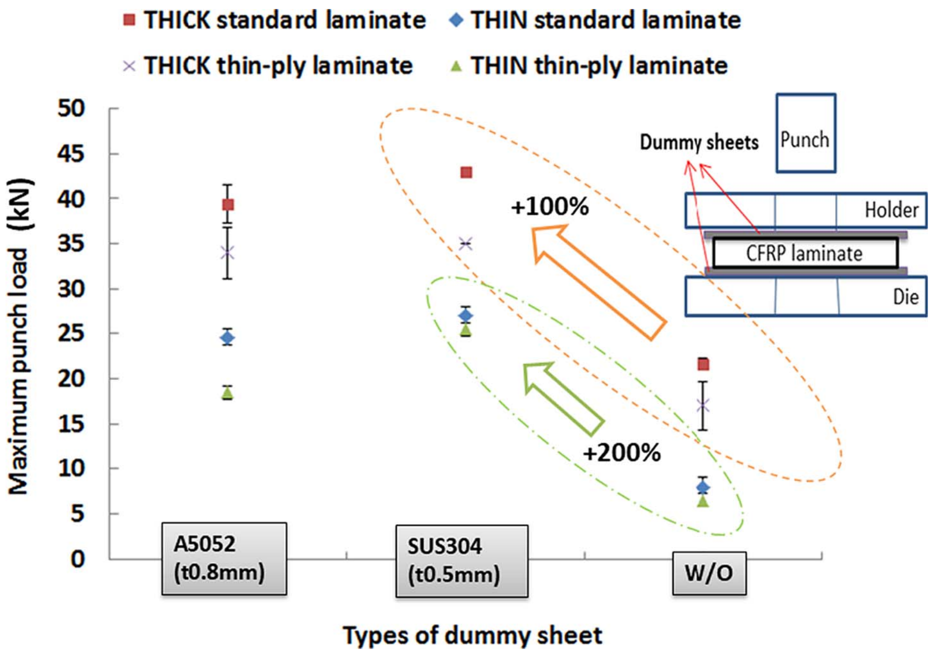


Fig. 8. Comparison of punching of CFRP laminates sandwiched with different dummy sheets.

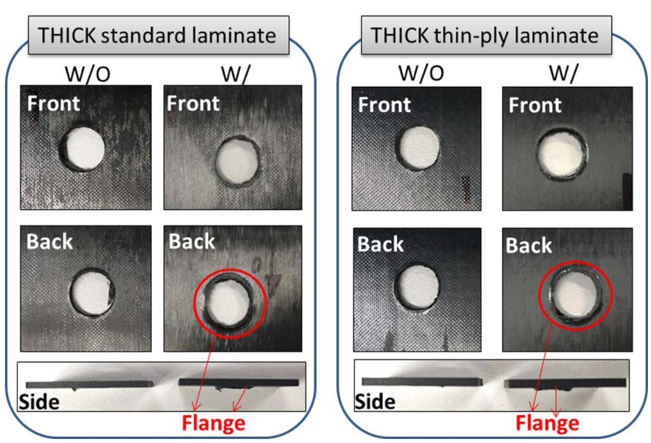


Fig. 9. Comparison of appearance of punched sample without and with A5052 dummy.

functional requirements, repair, maintenance, and so forth, and to prepare structures for subsequent operations. One of the most important aspects of the punching process is the shear mechanism, the knowledge of which is effective for understanding the shear behavior of a new material. Toward determining the shear mechanism, Fig. 7a and b respectively show side-view images of the deformation of the THICK standard and thin-ply laminates for half punches with strokes of approximately 25%, 60%, and 100% of the worksheet thickness. The details are shown and the features are discussed by considering schematics of these mechanisms and the corresponding images obtained in the experiments. Roll-over was initiated in the skin layers of the laminate, with subsequent shearing; inner and outer shear bands were formed in the proximity of the punch and die that were caused by the high transverse shear stress. Indeed, when both the standard and thin-ply laminates were half-punched, shearing initiated from the upper and back surfaces of the laminates simultaneously, later the shear bands extent through the thickness at similar characteristic angles. This caused a change in the diameter of the formed hole in the thickness direction. Namely, large propagation of the outer crack and the inner crack was connected by the delamination layer then produced an "N" shaped crack, as shown in Fig. 7c. Since the large propagation of the crack occurred in the outer portion, a protrusion of sheared scrap was observed. In the inner portion, peeling occurred on the back face of the sheared through-hole, peculiarly clear in thin-ply laminate was observed. Eventually, the specimens fractured through the fiber material at a similar characteristic angle and connected the inner and outer shear bands by a delamination that propagated between specific laminae. Thus, it can be concluded that the shear mechanism in the punching of multilayer CFRP laminates is very similar to that in both standard and thin-ply laminates. However, Fig. 7d shows that marked peeling off occurred close to the back layers appeared in the punched thin-ply laminate, where the peel height was almost half of the total thickness of the laminate.

3.4. Punching of sandwiched multilayer CFRP laminates

Dummy sheets are sometimes sandwiched between a workpiece and tool to improve quality and protect the workpiece in material forming [31,32]. Notwithstanding, Figs. 8, 9, and 10 show the unexpected results were obtained in experiments. For example, in the punching of THICK laminates with (W/) SUS304 dummy sheets, the processing force produces around 100% higher maximum punch load than that without (W/O) using the dummy sheets. Also, when the THIN laminate with SUS304 dummy sheets was punched, the maximum punching force was up to 200% larger than that without using the dummy sheets. Similarly, a 100% larger force was required for the punching of THICK standard and thin-ply laminates sandwiched with A5052 dummy sheets than for punching only a THICK CFRP laminate as shown in Fig. 8.

Fig. 9 shows the final appearances of punched THICK samples with both standard and thin-ply laminates. On the front surface, the shear region shows a relatively clean cut without using dummy sheets in the punching process. By contrast, a flange appeared on the back face of the punched through-hole for the punching of both standard and thin-ply laminates with A5052 or SUS304 dummy sheets as shown in the side view in Fig. 9. The process starts with rolling over the edge of the hole on the face sheet before actual shearing. Therefore, shearing of the intermediate layer, the THICK thin-ply laminate with A5052 on the right side of Fig. 10a clearly shows that the layers that were close to the upper skin were stretched in the shearing direction. The stretched-out geometry was occurred on the back surface of the sheared sample. Punching of sandwich materials by using skin sheet metal with reduced stiffness such as aluminum alloy, the roll over increases compared to steel face sheets [33]. Also, when the softer dummy sheets were used, a flange was clearly formed as shown in the experimental results on the

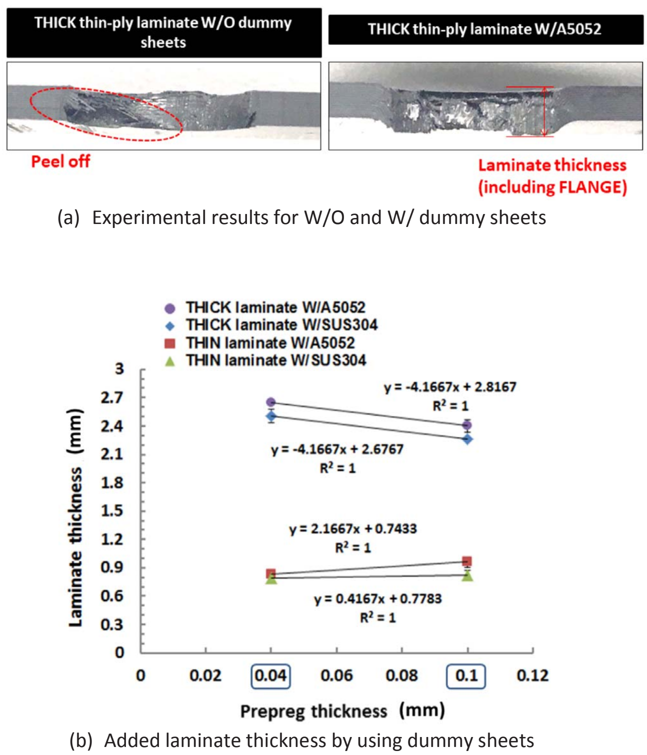


Fig. 10. Comparison of CFRP laminates with and without using dummy sheets.

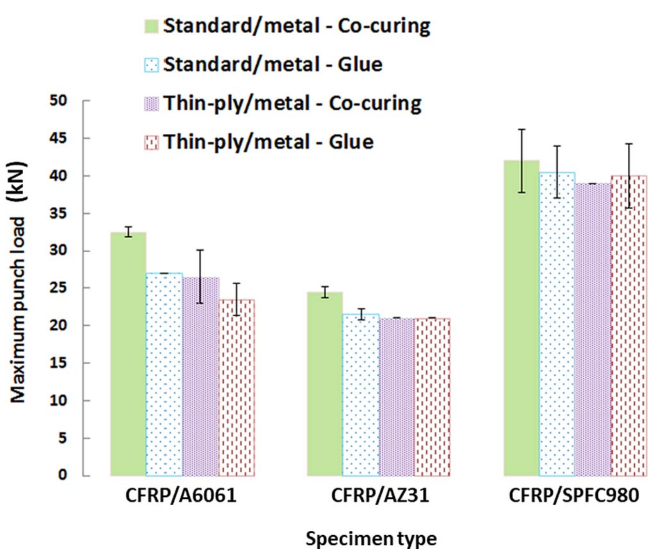


Fig. 11. Comparison of maximum punch force in hybrid composites.

Fig. 10b. However, we do not claim that it is unnecessary to use dummy sheets in the manufacturing processes. The successful press forming of CFRP sandwiched by dummy sheets was previously reported [31]. Dummy sheets have also been employed in single-point incremental forming to improve the forming quality [32]. Hence, in the present study, a flange even occurred on the back side of the tested sample in the punch-shear process utilizing the sandwiched dummy metallic sheets. The dummy sheets also improved the defects such as the peel off as shown in the right side of Fig. 10a (THICK thin-ply laminate W/A5052) compared with the punching of the THICK thin-ply laminate without using dummy sheets.

3.5. Practical applicability on punching of CFRP/metal hybrid composites

CFRP/metal hybrid composites consist of materials with diverse mechanical properties, lightweight design, and as a consequence replace monolithic structures in automotive parts such as B-pillar [1]. In this investigation, the punching of CFRP/metal hybrid parts was studied experimentally, and standard and thin-ply laminates in THICK samples as well as combined with A6061, AZ31, and SPFC980 metals by autoclave co-curing and glue bonding were fabricated as punching specimens.

Fig. 11 shows maximum punch load of each hybrid composite. Comparing the maximum punch force, the results generally show that the maximum punch load for standard/metal is more than that for thin-ply/metal. Namely, maximum punch force for thin-ply/SPFC980 with co-curing is 7% lower than standard/SPFC980 with co-curing owing to the decrease in the ply thickness from the standard value to 0.04 mm per layer. Even so, a similar maximum punch force to that for the CFRP/metal hybrid composites can be achieved by using glue adhesive instead of co-curing according to the experimental results, as also shown in Fig. 11. In view of CFRP/metal layered composites, the lower maximum punch force for standard/AZ31 compared to standard/SPFC980 which results in the strength of metal layer dominated the punch-shear load. The lower strength of the used sheet metal on the bottom layer reduces the maximum punch force for hybrid composites. As a result, maximum punch load is less for the thin-ply/AZ31 than for the thin-ply/SPFC980 hybrid composites. This higher maximum punch force obtained in CFRP/SPFC980 is owing to the high-strength steel sheet on the bottom layer. Therefore, the punch-shear load in CFRP/SPFC980 is highly required than in the hybrid composites made with CFRP and low-strength metallic sheet. In other words, punching of CFRP/SPFC980 exhibited larger punch force than in the CFRP/A6061 and CFRP/AZ31.

In the fact that maximum punch load is dominated on the under layer of CFRP/metal hybrid composite. In Fig. 12, different load-displacement curves for CFRP/metal hybrid composites are shown. As depicted for a thin-ply CFRP laminate, curves of *Ks* against the normalized displacement are shown for different specimens. The left side of Fig. 12 shows that there was a qualitative change in the curves when the thin-ply laminate was bonded on the high-strength SPFC980 steel. Thus, in the punching of the hybrid composites, load accumulated gradually in the ductile steel layer (the responses differ from punching of CFRP laminates). Then the next stage (the increase in the load to its maximum value) was due to the failure of the steel layer, which occurred later than the shearing of the composite laminates owing to its plasticity. It can be seen on the right side of Fig. 12 that the steel layer was rolled over by the CFRP laminates owing to the high shear force. In addition, as shown in the cross section of the punched thin-ply/SPFC980 hybrid composites on the right of Fig. 12, a partial CFRP sheared on the metal in the punching direction during the punching process, and it was found that the through-hole in the CFRP lightly clinched the metal after the punch-shear of the CFRP/metal hybrid composites. From the above discussion, it is beneficial to evaluate the punch-shear strength of CFRP/metal hybrid composites at the initial stage of the design. Fig. 13 shows punched CFRP/metal hybrid composites with a through-hole and punched samples with a sound profile and shear edges that were obtained in this study. However, standard/A6061 with co-curing cannot be bonded strictly after punching. This also occurred in standard/AZ31 with co-curing. In contrast, standard/SPFC980 and thin-ply/SPFC980 structures can be connected and punched more reliable, regardless of whether they are fabricated by autoclave co-curing or glue joining.

Another important issue in the punching of CFRP/metal hybrid composites is the bonding interface of the final product. In this work, CFRP/metal hybrid composites were fabricated by autoclave co-curing and using DEVCON PW I glue adhesive to clarify the difference between them after the through-hole punching process. Fig. 14 shows cross-

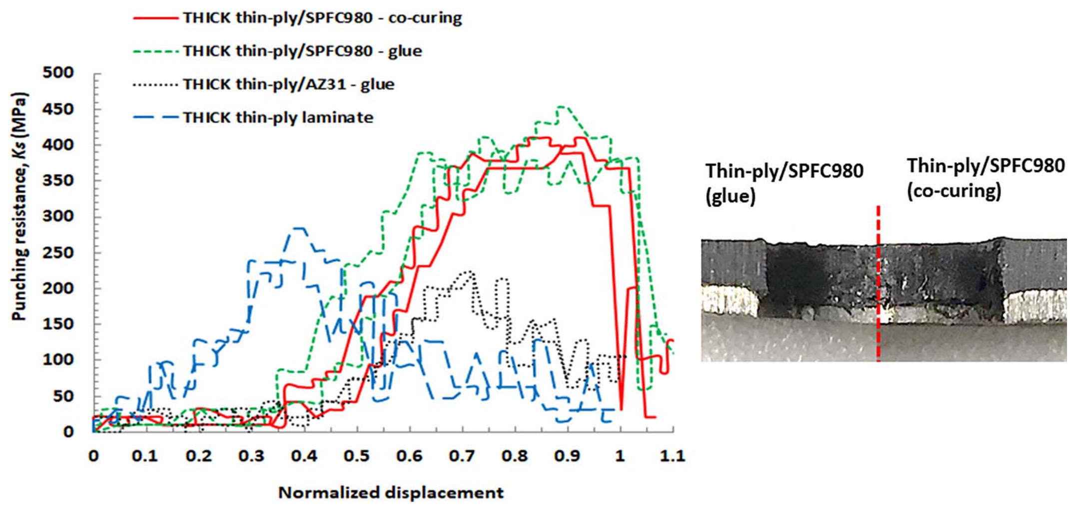


Fig. 12. Comparison of punched thin-ply/SPFC980 hybrid composites.

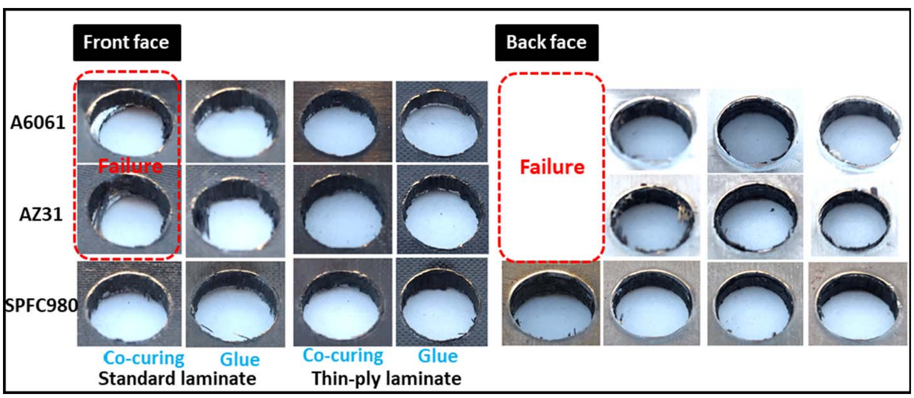


Fig. 13. Punched through-hole of CFRP/metal hybrid composites.

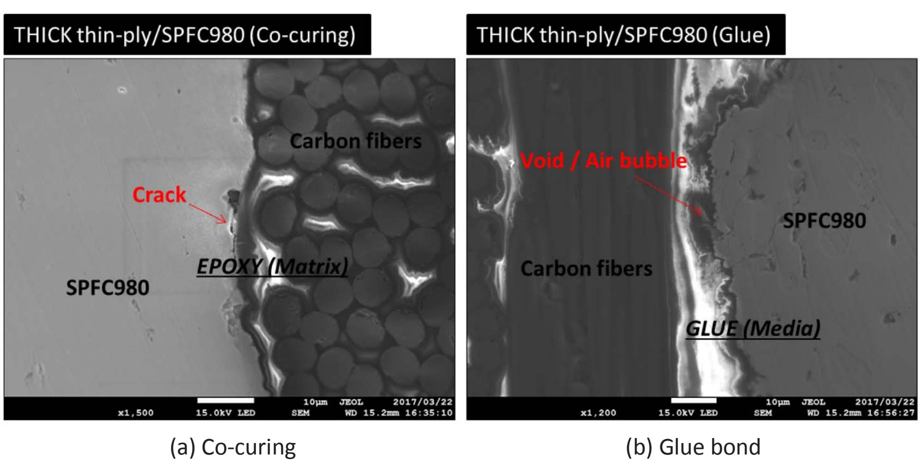


Fig. 14. SEM images of interfaces of punched THICK thin-ply/SPFC980 hybrid composites.

sectional scanning electron microscopy (SEM) images of the THICK thin-ply/SPFC980 specimens after the punching tests at a position near the sheared surface. Fig. 14a shows the crack between the epoxy resin and metal, which may have occurred when the co-curing method was used for CFRP/metal hybrid composites owing to the lack of robustness of the matrix. On the other hand, even though the glue successful connected the CFRP and the metal, the composite may have failed owing to the presence of voids and air bubbles as shown in Fig. 14b. Thus, a powerful joining method is also a critical issue at the design stage for hybrid composites.

4. Conclusions

The punching of through-holes on pseudo-ductile CFRP laminates and CFRP/metal hybrid composites utilizing a servo press was studied. The effect of the UD prepreg size on the punch-shear load, punching resistance (*Ks*), and the action of shearing was discussed on the basis of experimental results. The main points of this study are as follows:

- The punching of the laminate made with standard prepreg sheets resulted in a larger punch load than that for the thin-ply laminate, regardless of the punch speed and the thickness of the laminate.

Nonetheless, the experimental results indicate that the punch force has a linear relationship with the machine speed for the punching of laminated CFRP composites; the reference maximum punch load tended to decrease with increasing machine speed.

- The punching resistance (*Ks*) is considered to be a suitable parameter for evaluating multilayer CFRP laminates made with various prepreg thicknesses in terms of the ultimate tensile strength (σ_{UTS}) and yield stress (σ_y). The actual experimental results in this study were closely fitted by linear functions such as $Ks = -0.16\sigma_y + 386$ and $Ks = 0.59\sigma_{UTS}$-525 (37 SPM punching velocity). Hence, the maximum punch load is applied that allows a straightforward assessment for design purposes.
- The shear mechanism in the punching of laminated CFRP composites is very similar to that in both standard and thin-ply laminates. Standard and thin-ply laminates subjected to half-punching showed that shear cracks through the fiber material at similar characteristic angles by the punch for outer shear band and die for inner shear band, as well as the large propagation of the outer crack and the inner crack was connected by the delamination.
- Punching of standard and thin-ply laminates sandwiched by dummy metallic sheets as protective materials was performed, and high quality was expected for the resulting holes. Nevertheless, the use of softer dummy sheets resulted in a flange clearly appearing on the back face of the punched samples. However, punching with sandwiched metallic dummy sheets mitigated defects such as peel off that significant occurred in the punched thin-ply laminates.
- The proposed punching of a through-hole in CFRP/metal hybrid composites for functional use is expected to expand the range of industrial applications. Besides, the maximum punch load on punching of CFRP/metal hybrid composites is dominated by the strength of the bottom metallic layer, and it is valuable to assess the punch-shear force of CFRP/metal hybrid composites at the initial design stage. Hence, experimental results show that the interface bonding of punched CFRP/SPFC980 is reliable than the CFRP/A6061 and CFRP/AZ31.

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