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Enhancement of strength and uniformity in unidirectionally arrayed chopped strands with angled slits

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ABSTRACT

This study proposes a technique for enhancing strength and uniformity in unidirectionally arrayed chopped strands (Enhanced UACS). Enhanced UACS is made by introducing slits at small angles to the fiber direction into a unidirectional prepreg. As the angle becomes smaller, the stress concentration around the slit decreases. Therefore, delamination initiated from the slit is effectively suppressed and the final failure is mainly caused by fiber breakage. As a result, the Enhanced UACS laminate achieves excellent tensile, compressive, flexural, fatigue and impact strength, comparable to continuous fiber composites. Moreover, we demonstrate that the laminate can be uniformly stretched without a slit opening when it is formed.

1. Introduction

In recent years, application of fiber-reinforced plastic has gained considerable attention in transportation usage because reducing weight directly improves fuel consumption. In particular, sheet molding compound (SMC) is used in many components requiring a complex shape and high stiffness due to its excellent formability and its relatively higher volume fraction of fiber (Vf) than pellets/granulars for injection molding [1–3]. SMC is composed of randomly distributed chopped strands and unsaturated thermoset resin. SMC intrinsically contains many stress concentrations at the ends of the chopped strands. These ends are stochastically overlapped during manufacturing, becoming origins of failure due to the stress concentration. This is the reason for the low strength and the large dispersion of mechanical properties [4–13]. Therefore, its application has been limited to non-structural use due to safety concerns.

However, continuous fiber molding materials are difficult to form into complex shapes without time-consuming processes such as darting and piecing, even though they have highly useful and consistent mechanical properties. From the late 1980s, some companies, including Courtaulds Heltra [14] and DuPont [15–19] pioneered aligned discontinuous fiber yarn using stretch-breaking technologies, which are commonly used for making apparel yarns. Continuous reinforced fibers are broken in tension into short staples, and the staples are then aligned and recombined into yarns. Molding materials using these yarns could be stretched and formed wrinkle-free. The most prominent products are TPFL™ (Schappe Techniques) [15,20–23] and Stretch Broken Carbon Fiber™ (SBCF; Hexcel) [15,24]. TPFL is a series of fabrics such as dry prepreg and braids using commingled yarns. Stretch-broken reinforced fibers are pin drafted and spun with similarly broken fragments of thermoplastic filaments, resulting in commingled yarns. SBCF is characteristically coated by water-based epoxy sizing throughout stretch-breaking so it can be handled like ordinary continuous tows. Highly aligned unidirectional prepreg is produced with SBCF. In the other approach, Pepin Associates developed DiscoTex™, which is a woven fabric made of aligned chopped strands [15,25]. Two arrays of chopped strands of uniform length are placed in staggered positions and supported with continuous binder filaments. The binder will be washed out after the weaving process.

In previous papers [26,27], we proposed an other type of formable molding material, unidirectionally arrayed chopped strands (UACS). UACS is made by introducing slits into a unidirectional prepreg. This procedure enables making a sheet-like molding material constructed with regularly and unidirectionally arrayed discontinuous fiber strands impregnated with unsaturated thermoset resin. UACS allows the fiber strands to flow smoothly during molding, while the stress concentration is minimized by isolating the mutual positions of the strand ends. Complexly shaped components such as rib structures can be fabricated by stacking UACS plies and curing them into laminate by hot pressing in the same manner

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as SMC. In addition, the quasi-isotropic UACS laminate exhibits superior mechanical properties in comparison to those of SMC [26]. In the experiments, delamination is the main source of damage causing final failure in UACS laminates. Therefore, we proposed interlaminar toughening of UACS laminates to suppress delamination and demonstrated the resulting strength improvement [27]. However, the toughened UACS still fractured during delamination.

This study seeks to enhance the strength of UACS. We propose a UACS manufacturing technique of introducing slits at small angles to the fiber direction into the prepreg, as illustrated in Fig. 1. The slits of the UACS described in our previous papers [26,27] are in a direction perpendicular to the fiber. Therefore a large shear stress likely to cause delamination in mode II is applied to the slits. In contrast, slits having small angles decrease the stress and suppress delamination initiated from the slits. As a result, fiber breakage becomes the dominant factor for the final failure of UACS due to delamination.

In this study, we experimentally demonstrate that the tensile strength of UACS using carbon fiber increases toward that of continuous fiber composites as the slit angles become smaller. We define UACS with angled slits introduced as Enhanced UACS (Fig. 1) and compare its mechanical properties, such as tensile, compressive, flexural, fatigue and impact strength, using SMC, UACS with a slit angle of 90°, and prepreg. In addition, we find that the angled slits never open at a small angle during stretch forming.

This paper is organized as follows. Section 2 describes the angled-slit concept and the preparation of UACS. Section 3 discusses the superiority of Enhanced UACS in various mechanical properties. Section 4 analyzes the flowability of UACS laminates with visualization tests.

2. Angled-slit concept

As described in previous papers [26,27], UACS is made by introducing slits in a direction perpendicular to the fiber. Shear stress is generated around the slits in the 0° layers. Therefore, delamination easily initiates from the slits, and the resulting unstable growth of the delamination limits the strength of the UACS laminate. In this paper, we propose a slit having a small angle to the fiber direction for relaxing the shear stress around the slit.

Fig. 2 presents a schematic diagram of the angled slits. The illustrated 0° layer inside of the UACS laminate contains slits angled at θ° to the fiber direction and applied through the entire width of the lamina. Fig. 2 depicts an extracted microscopic square region including the angled slit. The average applied in-plane stress in the laminate σ can be divided into axial stress σ_x, σ_y and shear stress τ_{xy}, where the local coordinates, *x* and *y*, are respectively parallel and perpendicular to the slit. $\sigma_x = \sigma\cos^2\theta$, $\sigma_y = \sigma\sin^2\theta$ and $\tau_{xy} = \sigma\cos2\theta/2$ are derived from coordinate transformation. In the case of UACS ($\theta = 90$), σ_x, $\tau_{xy} = 0$ and $\sigma_y = \sigma$. Therefore, the stress applied to the slit in the direction perpendicular to the slit σ_y is maximized, so the shear stress around the slit is also maximized due to load transfer at the interface. On the contrary, in the case of UACS with a slit angled at a smaller θ, σ_x becomes larger and σ_y and τ_{xy} become smaller. σ_x does not contribute to delamination initiated from the slit because σ_x is parallel to the slit. σ_y and τ_{xy} cause the shear stress around the slits responsible for delamination in modes II and III respectively, but are not so severe that delamination initiates from the slits.

To confirm this concept, we obtained the relation between the strength of quasi-isotropic UACS laminates and the slit angles in static tensile tests. We made the UACS by introducing angled slits at designated angles into a unidirectional prepreg at intervals of 25 mm in the fiber direction. The slit angle to the fiber direction θ is 6°, 11°, 16°, 27°, or 45°. In this paper, a continuous slit is applied to eliminate singularities at the ends of dotted slits. We used an automatic cutting machine to mechanically introduce the slits into the prepreg using a tangential knife attached to the machine. The knife did not completely cut through the release paper attached to the prepreg, thus the cut prepreg could be handled even after introducing slits through its entire width. The prepreg used in this paper was P3052S-15 (Toray Industries), which is made of carbon fiber T700S and epoxy resin #2500. The areal weight of the carbon fiber is 150 g/m^2, Vf is 58%, the longitudinal modulus is 130 GPa, Poisson's ratio ν_{LT} is 0.34, and the longitudinal strength is 2460 MPa.

The UACS plies were prepared by cutting sheets (250 × 250 mm or 300 × 300 mm) out of the prepreg after forming the slits and stacking them in a quasi-isotropic lamination of $[45/0/\text{-}45/90]_{2s}$. The angled slit direction was set at $+\theta$ on the upper half of the laminate $[45/0/\text{-}45/90]_2$ and $-\theta$ on the lower half.

The stacked UACS plies were set into a mold cavity (300 × 300 mm) and cured at 3 MPa pressure and 150 °C for 30 min. For the stack with an initial size of 300 × 300 mm, the surface area did not change after hot pressing. In contrast, the smaller stack (250 × 250 mm) charged, filling the cavity (300 × 300 mm) to increase its area by 31%.

As benchmarks, we compared the tensile strength of these UACS laminates with conventional laminates made of unidirectional prepreg without slits ($\theta = 0°$) and UACS laminates with slits in a direction perpendicular to the fiber ($\theta = 90°$).

Conventional laminate was made by stacking the prepreg in a quasi-isotropic lamination of $[45/0/\text{-}45/90]_{2s}$ and curing in the same size. The UACS laminate was made in the same way as in the previous papers [26,27]. UACS plies have 12.5 mm width slits in the direction perpendicular to the fiber at intervals of 25 mm in the fiber direction. These plies were stacked in a quasi-isotropic lamination of $[45/0/\text{-}45/90]_{2s}$ and cured into the laminates either not stretched or stretched by 31% from the stack. Vf for the UACS was the same as for the prepreg (58%).

Fig. 3 presents the relation between the tensile strength of quasi-isotropic UACS laminates and the slit angle θ. These tensile tests followed the procedure described in ASTM D3039. The coupons were cut to 25 mm in width and 250 mm in length with a 150 mm gauge length. The grip parts were sand blasted and tested without tabs. The cross-head speed was 2.0 mm/min. The error bars in this paper correspond to ±*SD*, where *SD* is the standard deviation. As the slit angle becomes smaller than 45°, the tensile

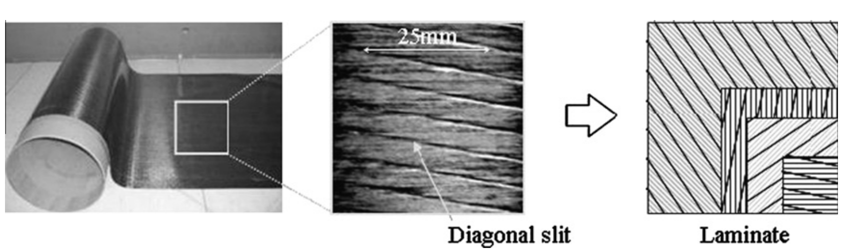

Fig. 1. Schematic diagrams of Enhanced UACS, created by introducing angled slits in arrayed continuous fibers of prepreg.