Effect of winding angle on impact properties of thin walled tubes

Z. KORINEK, J. CHROMY, LE HIEU GIANG, Z. JENIKOVA
Department of Materials Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, Karlovo nam. 13, 121 35 Prague 2, Czech Republic

Composite specimens with changing angle of filament winding (±0, ±10, ±20, ±29, ±45, ±60, ±70, ±80, and ±90°), made from carbon fiber (Torayca T700S) and epoxy resin PR 102 (producer 5 M s. r. o., Czech Republic) were investigated in this study. Charpy impact tests were performed on an instrumented pendulum hammer CEAST Resil 25. The mass of the pendulum hammer was 3.6747 kg, maximal velocity 2.9 m/s, maximal energy 15.375 J and distance of supports 40 mm. This distance of supports was not according to the ISO 179 standard because specimens with high winding angle (±70, ±80, and ±90°) were very flexible and remained unbroken at a standard distance of supports (60 mm). The tests were performed at room temperature.

The specimens were cut from composite tubes wounded onto a hexagonal mandrel in CompoTech s. r. o., Czech company. Gradual heating (temperatures from 20 to 95 °C, total time of heating 20 hr) of the tubes was used for curing of epoxy resin, without a pressure and a bleed cloth. The dimensions of the specimens for impact tests were 3 ± 0.1 mm and 10 ± 0.2 mm. The specimens were tested in flatwise position. Changes of voltage on a strain gauge in the striker edge were recorded by an A/D converter working under Disys software (Czech product). The voltage was converted into force. The strain gauge was calibrated only statically and no dynamic calibration factor was used [1].

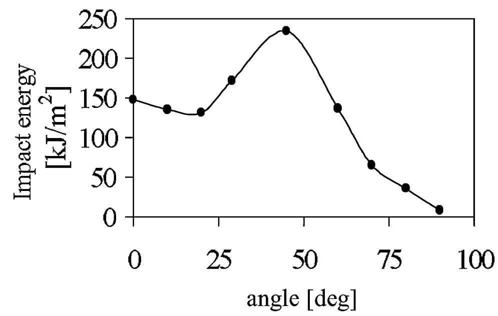

Figure 2 The impact energy unnotched specimens versus winding angle ±Θ°.

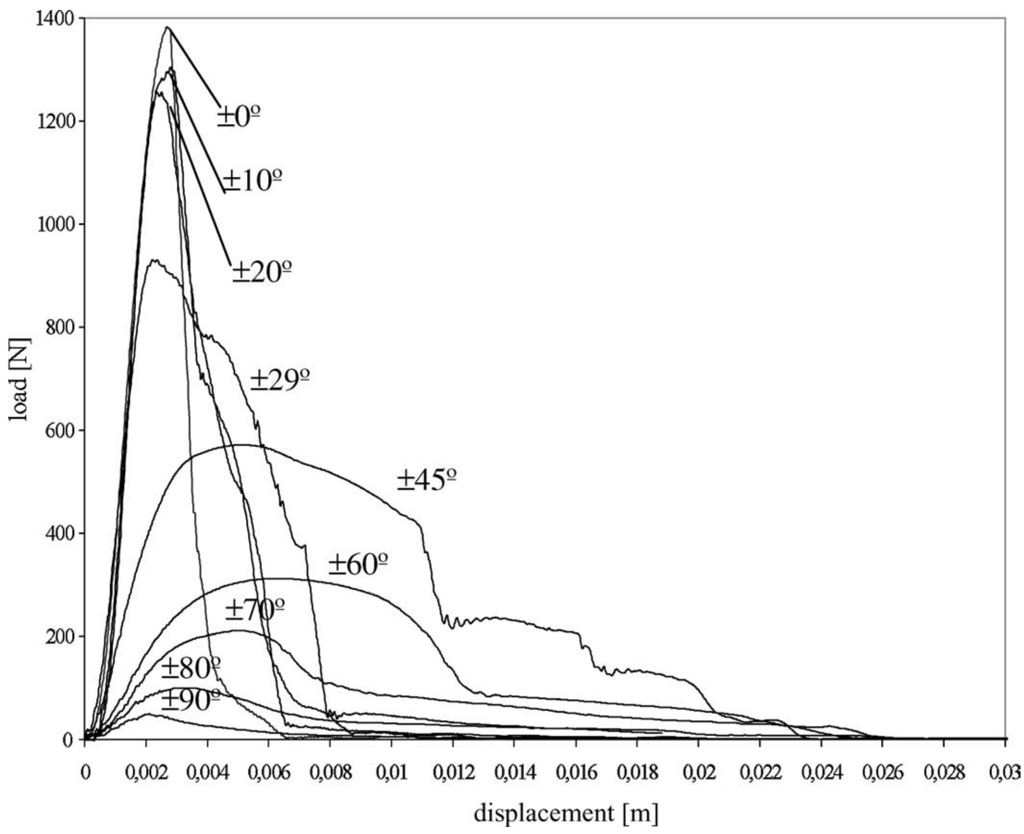

Figure 1 Smoothed traces of load versus calculated displacement for different winding angles ±Θ°.

0022–2461

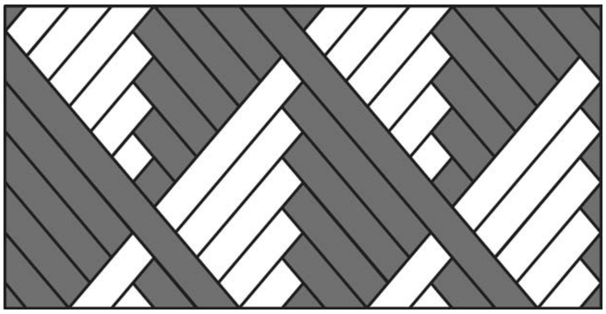

Figure 3 Winding patterns of angle ±45° (crossed rovings).

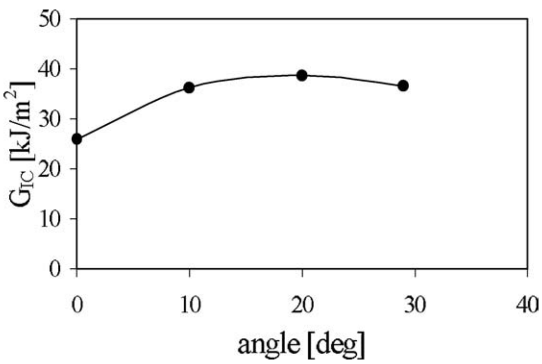

Figure 4 Variation of G_{IC} versus winding angle Θ.

The displacement was calculated by double integration. The primary stored digital data were plotted as force-displacement, velocity-displacement and energy-displacement traces by a home-written evaluation program (Visual Basic) on a personal computer [2]. Fig. 1 shows filtered (moving average method) signals of load versus calculated displacement for various winding angles $\pm\Theta°$. The impact energy of unnotched specimens is shown in Fig. 2.

The maximal impact energy (234.5 kJ/m^2) of wound specimens was observed at winding angle ±45°. This result is in contrast to impact energy of laminates where the maximal impact energy there is when fibers are oriented in a maximum stress direction, that is at ply orientation 0° (the minimum of impact energy was observed at an intermediate angle of ply) [3]. The differences result from different geometrical arrangement of rovings in laminates and wound composites (Fig. 3).

Low matrix shear strength cannot be exerted like in angle ply laminates. The result of crossed rovings is large energy dissipation due to extensive fiber/matrix debonding. In the ranges of ±0–±20 and ±70–±90°, the impact energy gradually decreases. In specimens with low winding angle, failure is initiated by fiber fracture. For flexible specimens with a large angle of

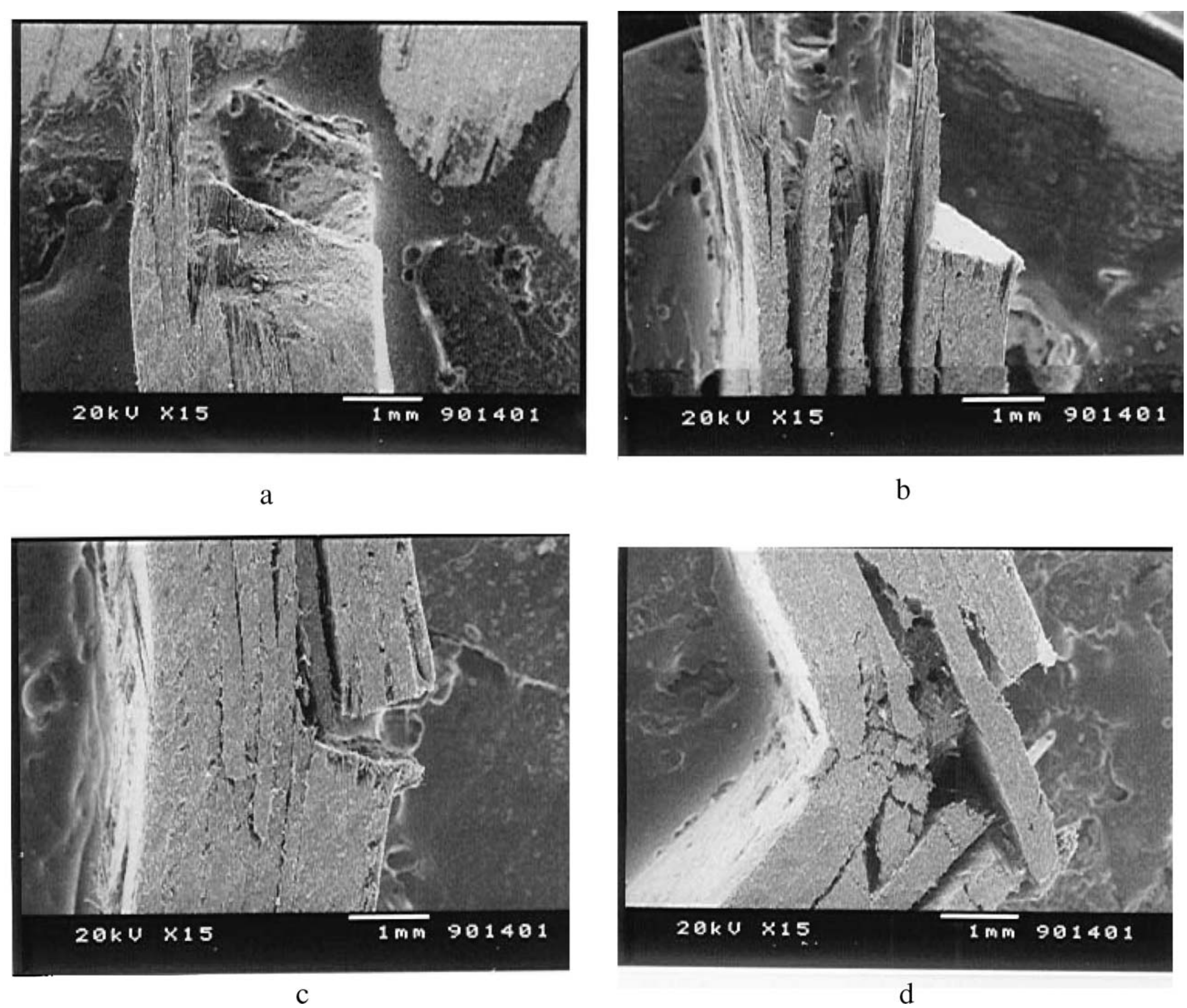

Figure 5 SEM micrographs of impact damage of tested specimens: (a) $\Theta = \pm 0°$, (b)$\Theta = \pm 29°$, (c) $\Theta = \pm 45°$ and (d) $\Theta = \pm 70°$.

winding (±70° and more), extensive delamination occurs, as seen in Fig. 5.

The effect of notch on impact behavior of the wound specimens was also tested. Sharp notches with a depth of 0–1.5 mm were shaved on the wide surface of the specimens. The parameters of the notch were: angle 25°; tip radius 0.015 mm. The maximal impact energy of notched specimens was also determined for the winding angle of ±45°.

Determination of elastic strain energy release rate G_{IC} from a slope of the $E - BW\Phi$ plot [2] is not valid except for specimens with low winding angle. The main cracks propagate lengthwise and delamination occurs under the notch tip in specimens with high winding angle. Fig. 4 shows G_{IC} for winding angles of ±0°, ±10°, ±20°, and ±29°.

The carbon fiber/epoxy wound specimens had an average fiber fraction $v_f = 49.3 \pm 0.3\%$ (determined from density of specimens). Since the elastic constants of unidirectional laminate are: $E_{11} = 114\,000$ MPa and Poisson's ratio $\nu_{12} = 0.27$ (determined by program Microlam [4], void content assumed to be 3%), the $G_{IC} = 25.9$ kJ/m^2 gives $K_{IC} = 56.6$ MPa$\sqrt{m}$ [5]. This fracture toughness of wound composite specimens is above K_{IC} of laminates (from 26.4 to 37.6 MPa$\sqrt{m}$) [6]. Filament winding produces fiber crossovers in the architecture of the parts; however, these structures are usually modeled as laminated $[\pm\Theta]_n$ lay-up. Our results show that such simplification is incorrect.

The tested specimens were coated by gold and observed by scanning electron microscope (SEM) Jeol JSM 5410. Differences in damage of the specimens with winding angles of ±0°, ±29°, ±45°, and ±70° are shown in Fig. 5.

Specimens with low winding angle (±0°, ±10°, ±29°) were broken to two parts, whereas specimens with greater winding angles remain unbroken. Delamination initiate in specimens ±29°. Specimens with winding angle ±45° remain unbroken but angle of permanent deflection is low.

Acknowledgment
This research was conducted at the Department of Materials Engineering, CTU in Prague, and supported by project MSMT No. 21220008.

References
1. J. P. TRONSKAR, M. A. MANNAN and M. O. LA, *Engng. Fract. Mech.* **69** (2002) 321.
2. Z. KORINEK, J. STEIDL and CH. PLASKOS, *J. Mater. Sci. Lett.* **19**(9) (2000) 729.
3. P. K. MALLICK and L. J. BROUTMAN, *Eng. Fract. Mech.* **8** (1976) 631.
4. KUNO K. U. STELLBRINK, Micromechanics of Composites, Composite Properties of Fibre and Matrix Constituents, Hanser Publisher (1996).
5. F. L. MATHEWS and R. D. RAWLINGS, "Composite Materials: Engineering and Science" (Chapman & Hall, 1993).
6. C. E. HARRIS and D. H. MORRIS, *J. Comp. Techn. Res.* **7** (1985) 77.

Received 19 June 2003
and accepted 10 February 2004