Residual Stress Analysis in Composite Interleaves

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Particle Toughening Timeline

First instance of rubber toughening: Addition of butadiene rubber to polystyrene involved in a heterogeneous material with significantly improved toughness (Howard – 1965).

1950

First rubber toughening of epoxies: General Motors laboratory (USA) identified improved elastic effect of butadiene (SP) rubber added to improve toughness (Sulkin – 1968).

1969

Microencapsulation and plastic hole growth: Fractographic evidence suggested that rubber particles contained in the matrix were not homogeneously distributed and a mechanism for toughening was responsible for the toughness achieved (1973).

1973

Thermoplastic used in epoxy formulation: Thermoplastics such as polyurethane (PU) were added to the powders to increase toughness. Researchers rapidly began to investigate methods of controlling the phase morphology of the PU, but without any significant improvements in toughness (Burkitt – 1986).

1983

Interleaf toughened composites: Laminates of high toughness resin added between layers resulted in a significant improvement compression after impact strength (Odagiri – 1987) and G<sub>11</sub> and G<sub>12</sub> (Olah – 1986).

1987

Reduced constraint due to cavitation: The internal stress state ahead of the crack causes rubber particles to separate and act as stress concentrators releasing plastic shear yielding. Cavities also reduce constraint on the surrounding matrix and allow yield strength to be dependent on size, leading to stress raiser and reducing toughness. This is evidenced by the significant toughness increase when comparing between cavitated particle sized of the size from, plastic and close to or completely further from the particle.

1983

Micro scale residual stresses must be considered:

If the effect of the stress state around particles is to be understood then residual stresses from processing must be taken into consideration. These can be investigated using pure particle models to show how differences in coefficient of thermal expansion between the resin and the particle and resin shrinkage can lead to the build up of stresses during a processing cycle. The result for a cure hardening linear elastic model (left) and a pseudo viscoelastic model (right) of a single thermoplastic particle in epoxy are shown below.

Future work:

- Resin characterisation
  - Cure kinetics
  - Coefficient of thermal expansion
  - Cure shrinkage
  - Thermal properties

- Model validation
  - CT DIC experiment to determine the strain field development around a particle during processing

- Fracture testing and fractography
  - Fracture testing of interlaced composites reinforced with different particulate materials
  - Comparison of crack paths and toughness

Key Question:

Why do particles keep crack within interleaf?

Particles are acting as more than just a spacer and are capable of keeping cracks within the interleaf and hence realising the lamina toughness. Numerical studies have shown that cracks are drawn towards particles when an opening displacement is applied (Stevanovic – 2005, Borstar et al. – 2016). This is indicative that the particles are acting as stress concentrators and the interaction between the crack tip and particle stress fields drives the crack towards the particle.