DEVELOPMENT OF ATL AND MATERIALS FOR LOW COST PRODUCTION

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1 Introduction

The Automated Tape Laying (ATL) process is typically used for high performance parts in the aerospace industry with the advantage of reduced labour, increased part quality and consistency. The process involves robotic placement of relatively narrow strips of prepreg. Typically, the prepreg is heated and the backing tape is removed, it is then positioned and cut accordingly. These operations occur continuously within a material delivery head. Typical ATL materials consist of high cost high modulus carbon fibres impregnated with a high performance high cost toughened epoxy resin. The performance material is laid into high stiffness precision alloy moulds. The ATL process is now being developed for low cost applications such as wind turbine blade production where an increase in deposition rates and a reduction in material costs are necessary to improve the financial attractiveness of the process.

ATL lay-up of new low cost materials was found to be problematic in comparison to existing aerospace materials. The difficulties were mostly attributed to a change in material tack levels where the machine relies on tack to the mould surface or subsequent plies exceeding the tack to the carrier or backing paper (Fig 1-1). The high compaction force believed to increase tack [1] was also found to cause significant deflection in wind energy mould tooling. Tack levels were therefore investigated using a previously defined method [2] and compared to ATL performance and resin rheology.

2 ATL Trials

A Cincinnati V4 contour tape layer (CTL) machine was used to perform all lay-ups. The machine was shown to be capable of cutting and laying intricate tape pieces over a curved alloy aerospace tool using Aerospace tape comprising of 8552 resin and 200gsm AS4 carbon fibres. However, successful lay-up required some experimentation with increased temperature and the use of tackifier.

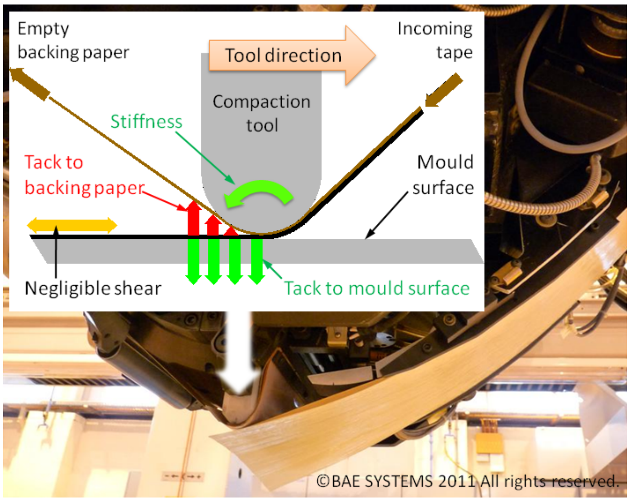

Fig 1-1. Force diagram of the ATL process shown against a Cincinnati V4 CTL delivery head

E-glass fibres were then impregnated with a wind energy grade resin system to produce low cost ATL tapes. Fibre Aerial Weight (FAW) was increased from 200 to 600 g/m² to help increase deposition rates. A number of resins were utilised, formulated for ‘low’, ‘medium’ or ‘high’ tack levels.

New materials were laid into a 7m aerofoil section composite mould tool where the shape and construction methods reflected those used by the wind turbine blade manufacturing industry.

2.1 Results

Lay-up of new materials was found to be increasingly difficult in comparison to existing aerospace ATL tape and attributed to three main problem areas; Cutting, release from the backing paper and tack to the mould surface.

Cutting issues were attributed to a build up of resin on the cutter tip (Fig 2-1) and were alleviated with a change in cutter blade geometry. Resin build up continued with the new cutter although away from the tip allowing cutting to continue. Lay-up was paused regularly to remove the resin build up preventing it from dropping off into the laminate. To reduce resin build up the resin content was limited to 28% by weight. Cutter issues were not investigated further as they were found to be alleviated completely with the use of ultrasonic cutters with which the latest machines are equipped as standard.

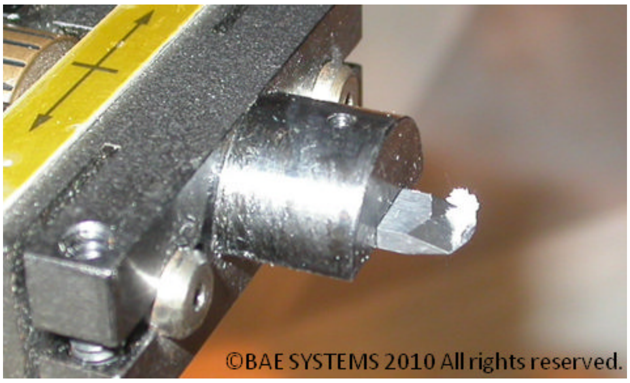

Fig 2-1. Resin build up on the cutter tip found when using low cost ATL tape

Poor lay-up performance was found when using ‘high’ and ‘medium’ tack resins attributed to poor release from the backing paper. Additionally, ATL operators believe that manual intervention is always required and found to be increasingly difficult as tack levels increase. Therefore, low tack resin systems were preferred. These low tack tapes were found to be difficult to lay-up due to poor adhesion to the mould surface which became increasingly difficult with the use of mould release agents. Subsequently, in-house tackifier was required to give adequate tack to the mould surface for successful lay-up of the first ply. Poor mould adhesion also increased the risk of the entire lay-up shifting in position or being lifted entirely from the mould surface during subsequent plies. Therefore, the operators preference to low tack material for manual handling capabilities appears to increase the probability that manual intervention is required.

The new materials were laid into low cost glass epoxy moulds typical of those used in the turbine industry. The moulds were subsequently found to deflect under the high (265-1300N [3]) compaction force of the tool head causing the ATL to halt due to alignment issues.

Overall ATL was successfully used to produce a 7m representative section of a 45m wind turbine blade (Fig 2-2). However, mould deflection and tolerance issues limited each ply to 60-75% automated lay-up with the rest of the ply finished by hand. Further research is now required to avoid the use of tackifier and manual intervention due to lay-up failures resulting from inadequate tack to the mould surface or poor release from the backing paper, all of which were found to reduce the overall achievable deposition rate.

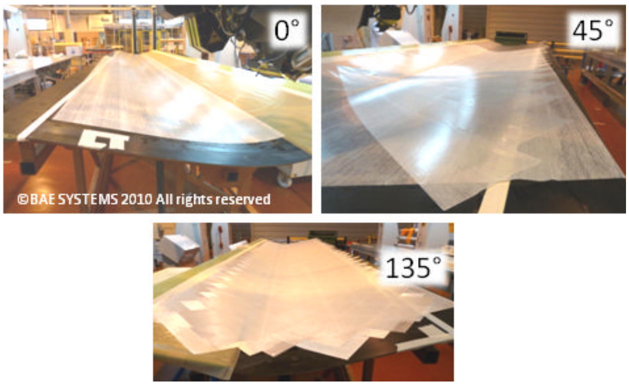

Fig 2-2. ATL lay-up achieved over a curved 7m representative wind turbine blade mould tool

3 Tack testing & rheology

3.1 Method

A newly developed peel test method, which simulates the ATL process, was utilised to compare new ATL prepreg materials [2]. The prepreg is pulled through rollers against a rigid substrate with a compaction force applied. The covered prepreg is measured first which gives dynamic bending stiffness. The test then moves continuously onto a non covered section measuring peel resistance. Dynamic stiffness is subtracted from the peel resistance to quantify the tack level (Fig 3-1). The effects of temperature, resin type, FAW, fibre type, compaction pressure and release agents were studied on tack and compared with the effect of temperature on the rheological dynamic storage modulus of resin only samples taken from the prepreg.

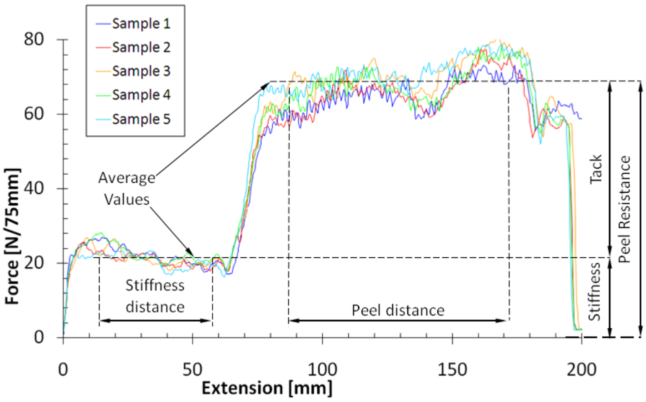

Fig 3-1. Typical peel test results and analysis of medium tack ATL E-glass tape

3.2 Results & Discussion

Both aerospace and new low cost e-glass ATL tapes showed a transition between two failure modes, distinguished by differences in resin deposition patterns and the formation of fibrils (Fig 3-2). The failure modes were consistent with pressure sensitive adhesives (PSA) peel [4] where failure at the surface with little resin deposition is termed 'interfacial failure'. In contrast, failure within the resin leading to significant resin deposition is known as 'cohesive'. The failure modes are also consistent with those previously identified in ATL like apparatus [5]. These failure modes are also associated with the viscoelasticity of the resin in the PSAs viscoelastic windows principle [4].

Despite the similarities in observed behaviour between the two tapes, a significant difference in tack response was found (Fig 3-3). The tack of aerospace tape remained low with only a minor peak observed at the failure mode transition of around 55°C. Low cost E-glass tape revealed a significant peak in tack around the failure mode transition temperature of 27°C.

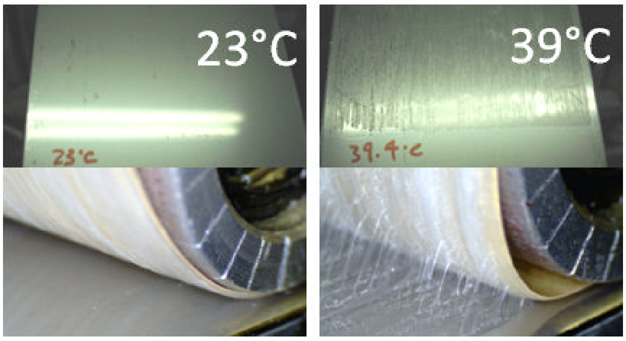

Fig 3-2. Interfacial (left) and cohesive (right) failure modes found in E-glass ATL tape peel testing.

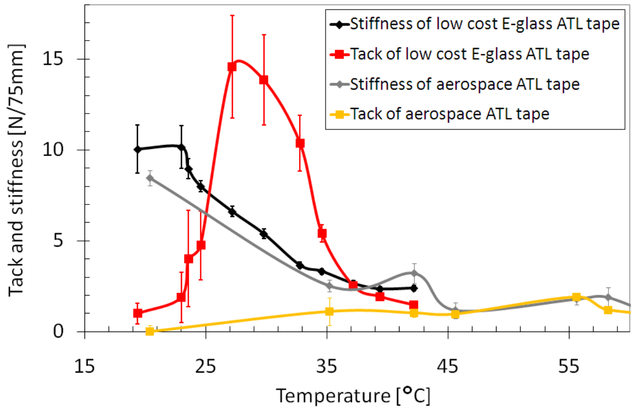

Fig 3-3. The tack and stiffness response of aerospace and low cost E-glass ATL tapes

Two tapes of equal resin type and content by weight were compared with alternative fibre types (Fig 3-4). The carbon fibre tape displayed consistently lower tack over a temperature range. The reduction in tack was attributed to a lower resin volume fraction due to the lower density of carbon fibres resulting in a change in impregnated resin distribution. However, significant resin deposition continued to be observed at the plate surface. Therefore, other possibilities such as failure at the resin-fibre interface or an electrostatic effect [5, 6] could not be ruled out.

Three tapes of equal FAW and E-glass fibre type with alternative 'high', 'medium' and 'low' tack resin systems were also compared at ambient temperature (Fig 3-5). The results showed good agreement with suppliers specified tack levels with little effect on prepreg dynamic stiffness.

A change in fibre areal weight (FAW) with constant resin type and content revealed an almost linear increase in tape stiffness (Fig 3-6). Tack level appeared moderately reduced without any significant trend possibly due to fluctuation in resin impregnation and surface distribution.

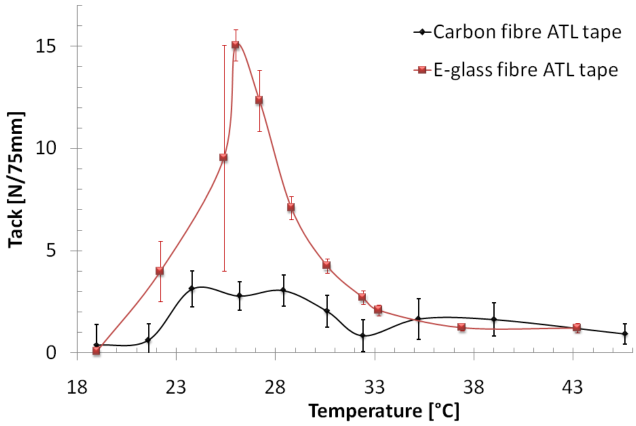

Fig 3-4. The tack and stiffness response of E-glass tape in comparison to carbon fibre

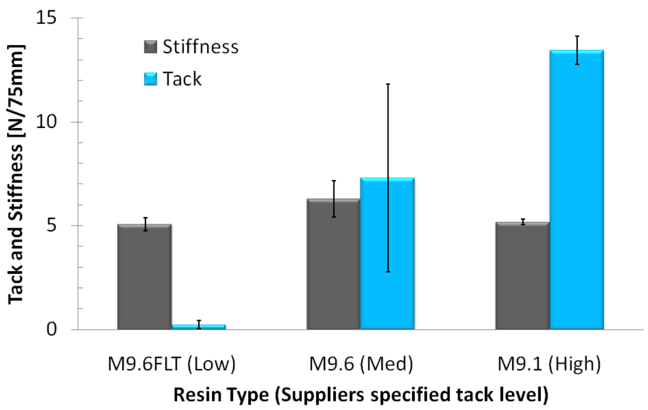

Fig 3-5. The tack and stiffness response of E-glass ATL tapes with alternate resin tack levels

The effects of compaction force on E-glass ATL tape over a temperature range were also characterised (Fig 3-7). Compaction force was found to be effective only in the region of peak tack, where the transition between failure modes occurs. Therefore, compaction force is thought to effect tack by deforming the resin layer to the microscopically rough surface increasing the actual contact area. At lower temperatures the resin is stiffer and increased compaction force is not adequate to cause the required deflection. At higher temperatures the resin is viscous and contact is mostly fully developed with increasing compaction force having little effect.

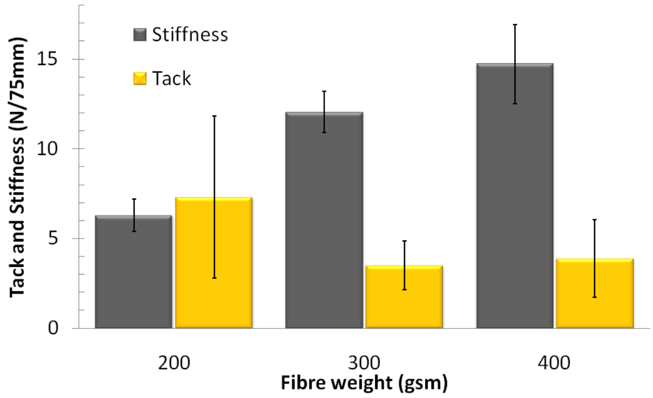

Fig 3-6. The tack and stiffness response of E-glass tape with alternate fibre areal weights

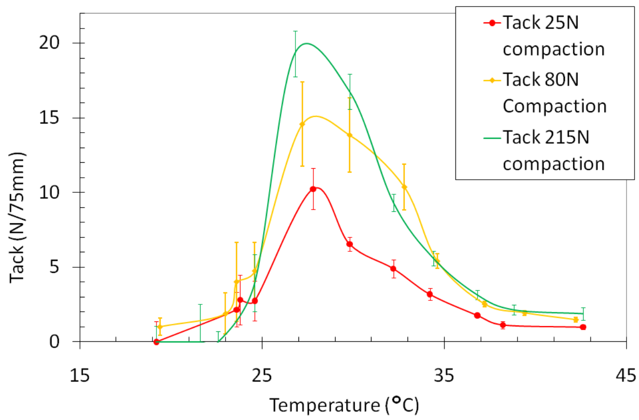

Fig 3-7. The tack and stiffness response of E-glass tape with increasing compaction force

The effects of release agents were also characterised on low cost E-glass ATL tapes. The results show that tack is significantly reduced over the temperature range (Fig 3-8) which confirms the findings of ATL operators who found it increasingly difficult to lay-up in the presence of release agent. The release agent appears to work by preventing adequate contact at the surface, observed by resin deposition, until a much higher temperature is reached by which point the resin too viscous to hold any significant load (Fig 3-9).

Rheology experiments on the resin only specimens taken from the prepreg showed an apparent stiffening of the epoxy when formulating lower tack resins, indicated by an increase in dynamic shear storage modulus. The increased stiffness results in lower tack by preventing surface adhesion according to the Dahlquist criterion [7]. The temperature sensitivity of the low cost epoxies in comparison to the aerospace resin is increased (Fig 3-10), which according to the time temperature superposition principle, also indicates that feedrate sensitivity is increased [7]. This is likely to account for the increased difficulty experienced throughout the operating range of ATL lay-up using low cost epoxy resin tapes.

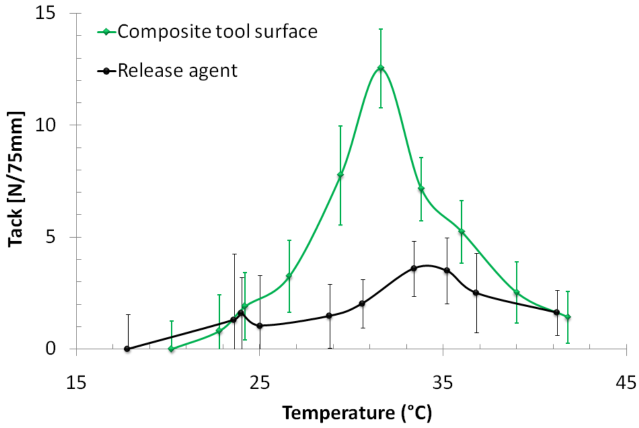

Fig 3-8. The effect of release agent on the tack of low cost E-glass ATL tape

The rheology results also give some indication of how tack is controlled by changing the viscoelasticity of the resin component at ambient conditions. The temperature sensitivity of the resin also highlights how changes in ambient temperature can affect lay-up performance, where a low tack resin can be of equal viscosity to a high tack resin with only a 7°C increase in temperature.

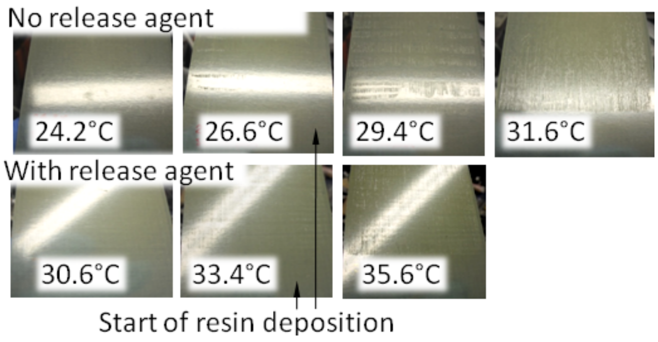

Fig 3-9. Release agent preventing resin deposition until a higher temperature is reached

The results of the compaction force and fibre type experiments also highlight the additional effects of surface conditions. A change in actual contact area may be achieved by a change in surface resin layer conditions, through a change in resin impregnation distribution or by resin deformation under an applied force. It appears that changes in surface variables may be ineffective where complete contact always occurs or forces are inadequate to deform the resin layer. Release also appears to act as a weak boundary layer preventing actual surface contact.

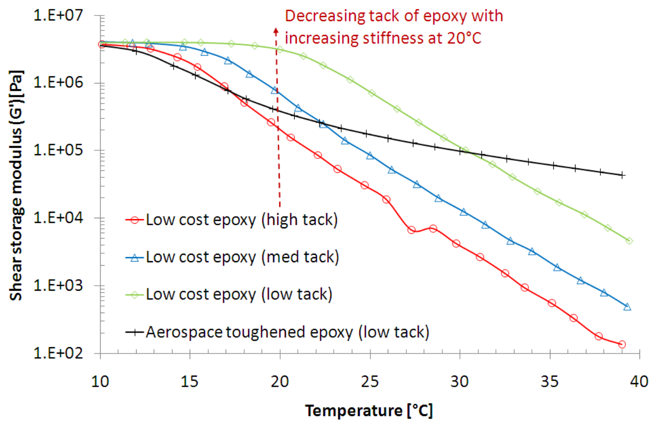

Fig 3-10. Dynamic storage modulus of low cost epoxies in comparison to toughened aerospace epoxy

4 Conclusions

Successful ATL appears to rely on a fine balance of adequate tack to the mould surface and good release from the backing paper. Increasing the tack of prepreg improves mould tack at the expense of making release from the baking paper more difficult. Increasing the stiffness of the prepreg appeared to help release by aiding separation from the backing paper as it resisted bending around the tool head. The use of release agents appears to significantly reduce the available tack at the mould surface. Therefore, lack of tack to the mould surface became the most challenging issue. Increasing prepreg tack appeared ineffective as it only increased tack to the backing paper resulting in poor release. A high stiffness low tack prepreg was eventually favoured for good backing paper release. A tackifier was then used to overcome the issue of poor mould tack.

Newly developed low cost E-glass ATL materials were increasingly problematic during lay-up in comparison to existing aerospace tapes. This appears to be due to an increased sensitivity to temperature and therefore feedrate. The increased tack sensitivity appears to be the product of resin viscoelastic properties consistent with the findings of existing pressure sensitive adhesives research. Suppliers also appear to be controlling resin viscosity to give the required tack level at ambient conditions yet minor changes in temperature (+7°C) can also see viscosities change from the 'low' to the 'high' tack level accounting for the sensitivity of the ATL process to ambient temperature conditions.

Glass fibres also show significantly increased tack in comparison to carbon fibres, again indicating that high tack may be problematic to ATL resulting in poor release from the backing paper. Increasing fibre aerial weight shows no significant effect on tack but did increase material stiffness. The increased stiffness tape was preferred as it did appear to release much easier, coming away from the backing paper as it resisted bending around the tool head.

Compaction pressure was found to be ineffective at increasing tack outside of a narrow temperature range (25-35°C) which corresponds to the transition in failure modes. Within this temperature band significant levels of tack can be achieved with as little as 80N compaction force, indicating that ATL lay-up on low cost low rigidity mould tooling is possible with reduced compaction pressure provided the optimum lay-up conditions for the material are maintained.

Overall the performance of the ATL machine appears to be mostly dictated by the material behaviour and its response to variables which effect surface or viscoelastic properties. In this instance rheology and peel testing results were used to rationalise the difficulties found in selecting a new resin and fibre type suitable for ATL lay-up. A more integrated approach is now recommended for future development where peel testing can be used to identify optimum tack conditions for lay-up. Rheology results can be used to estimate the materials response to changes in temperature, feed rate and the effects of aging. ATL reliability could also be improved significantly with the development of a release agent which allows tack to the mould surface at the time of lay-up, perhaps thermally activated during the cure cycle.

5 Acknowledgements

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