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Manufacturing of composite parts reinforced through-thickness by tufting

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ABSTRACT

The paper aims at providing practical guidelines for the manufacture of composite parts reinforced by tufting. The need for through-thickness reinforcement of high performance carbon fibre composite structures is reviewed and various options are presented. The tufting process is described in detail and relevant aspects of the technology are analysed such as: equipment configuration and setup, latest advances in tooling, thread selection, preform supporting systems and choice of ancillary materials. Effects of the process parameters on the preform fibre architecture and on the meso-structure of the reinforced component are discussed. Special emphasis is given to the different options available in terms of tuft insertion and loops management.

Potential fields of application of the technology are investigated as well as the limitations of its applicability in relation to preform nature and geometry. Critical issues which may arise during the manufacturing process concerning thread insertion, loops formation, alteration to the fabric fibres layout or local volume fraction are identified.

1. Introduction

The growing use of composite materials for structural and semi-structural components in the aerospace, defence, transportation, civil and energy sectors has dictated the need for the development of automated manufacturing systems capable of producing, at the required rates, large, often complex, and high-performance parts. The unique manufacturing processes involved in composite parts production require the development of specialised technologies and the design of dedicated machinery. Generally speaking, the production line must account for the transformation of long filament fabrics (typically available as broad goods) into 3D shaped, resin impregnated, solid parts: this involves cutting plies out of the fabric roll, stacking them up over suitably shaped moulds, forming each ply individually to the required geometry, and finally curing the polymeric resin to embed the fibrous reinforcement is a consolidated matrix. The dexterity needed for such operations makes it challenging to devise automated processes which would replicate the functions of skilled operators; nevertheless the adoption of robotic manipulators and much specialised end-effectors is making this possible. Engineering companies now focus on the development and commissioning of full lines for the preforming, curing, machining and assembly stages of the composite part production.

In conventional composite laminates, the 2D fibre arrangement across the individual plies and the inherent brittleness of highly cross-linked matrix resin, makes the part subject to cracking in the interlaminar region between adjacent fibrous plies. This is the most likely consequence not only of direct out-of-plane loads, but also of high energy impacts. Good impact resistance is achieved through the minimisation of the damage extent within the composite structure, which in turn makes the structure more damage tolerant, by reducing the likelihood of progressive growth of the crack (or cracks) to a size which will cause structural failure. Several techniques are currently available to enhance the delamination resistance of polymer matrix composites. The manufacturer's selection of a particular technique over the others depends also, among other factors, on the primary composite manufacturing method involved and must be taken into account in the design of the automated system for the composite component production.

One well established method for improving damage and delamination resistance of composites is through resin toughening [1], which promotes phenomena like crack blunting, crazing, particle cavitation, shear banding and void coalescence as energy absorbing mechanisms [2,3]. Systems based on blends of polyethersulphone

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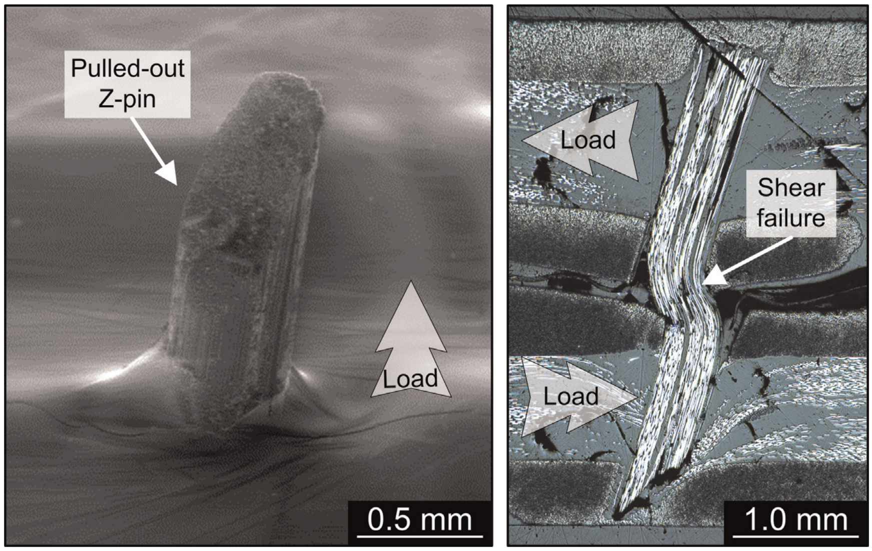

Fig. 1. On the left: SEM of chamfered portion of carbon Z-pin after frictional pull-out from the embedding carbon/epoxy laminate. On the right: cross-section of the Z-pin partially failed in shear.

(PES) and polyetherimide (PEI) were identified in the 1980s [4,5]. Other effective resin systems were developed in those years, such as polyetheretherketone (PEEK) and polyphenylenesulphide (PPS), which would also satisfy the requirement of the primary structure for high stiffness and strength. However, these systems were both high cost and difficult to process, having high melting temperature and needing high mould tooling pressures [6]. An alternative approach was developed by Toray in the early 1990s for the Boeing 777 aircraft in which thermoplastic particles were applied to the surface of epoxy resin/carbon fibre prepreg [7]: the prepreg type Toray 3900-2 proved very effective for damage resistance, although at a higher cost than standard prepregs.

Alternative, non-resin type toughening approaches use embedded reinforcing elements, sometime referred to as *micro-fasteners*, through either part of the laminate or the complete thickness of the assembly to reduce the risk of plies delaminating or disbonding. Once a three-dimensional fibre architecture is obtained, delamination or disbonding requires the pull-out or breakage of such micro-fasteners [8–13].

One technique which provides the part to reinforce with an extra load carrying medium through its thickness is Z-pinning [8], which was developed in the U.S. by Foster Miller, then Aztex, now Albany International, and involves embedding an array of thin[1], rigid pins (or Z-Fiber®) through the laminate or assembly before its final cure in autoclave. Once embedded in the cured part, the pins must be broken, pulled out or at least heavily deformed to allow crack growth (Fig. 1). This has been proven to be a very efficient technique, and cost-effective compared to using conventional mechanical fasteners [14]. However, it is a complex method, involving mainly manual operations and specifically developed for prepreg structures, since the inserted pins are held in place by the uncured matrix.

Three-dimensional weaving technologies certainly address the problem of delamination at its root albeit being cost-effective mainly at higher production volume, when manufacturing large scale, continuously 3D reinforced laminates. Their inability to provide preform taper without unacceptable fibre wastage or to provide easily tows at 45° severely limits their field of application.

Stitching is well suited to preform-type processing: it is both simple and relatively low cost, while lending itself to localised Z-reinforcement of sections in the composite with high out-of-plane stress state [15]. Early stitching research focused on conventional sewing, using two interlocking threads [16–19]. This was proven to be very effective for damage resistance by the NASA stitched wing programme in the late 1980s, but required extremely high sewing machine investment. The high cost of the unit was due not only to the scale and complexity of the equipment but also to the need of accessing both sides of the preform being reinforced to interlock the threads [20]. More recently, variations on this theme have been exploited such as stitching technologies which only require access from a single side of the structure, usually referred to as one-sided stitching technologies (Fig. 2).

Tufting represents the simplest version of the one-sided stitching approaches and it is specifically designed for the dry preform/liquid resin moulding process route. It represents a further stage, prior to the resin infusion process, in the manufacturing procedure; nevertheless, it may be considered a relatively economical method of obtaining a three-dimensional fibre architecture [25].

Originally an ancient method for carpet and warm garments manufacturing, tufting has now become a commercially available technology for through-thickness reinforcement (TTR) of thermosetting polymer matrix composites. It involves the insertion of additional tows, via a single needle, through the layers of a laid-up dry preform. The tows can be fully inserted (Fig. 3a) or applied to a partial depth through the preform thickness (Fig. 3b), orthogonal to the preform surface or angled (Fig. 3c). When the needle penetrates the whole preform thickness, a loop of yarn is formed on the underside of the structure. The loops are not tied or interlocked and the tufts remain in position because of the natural friction between the fabric and the thread. This technology requires access from a single side of the preform, which makes it ideally suitable for local, tailor-made reinforcement of complex, three dimensional shapes. In this paper a feasible manufacturing procedure will be outlined, in the form of practical guidelines, for the production of tufted composite materials. The mechanical performance and the failure mechanisms of the tufted composite are covered elsewhere [26–30].

2. Scope of through-thickness reinforcement methods

In principle, all TTR technologies represent valid methods to reinforce structural joints, as well as a potential alternative to

[1] Available diameters are 0.28 mm or 0.51 mm.

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