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Review

Three-dimensional needle-punching for composites – A review

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ABSTRACT

The current literature on three-dimensional (3D) needle-punched composites tends to address the aspects of preforms fabrication and composites characterization respectively. This paper aims to bring together these two aspects to provide readers with a comprehensive understanding of the subject of 3D needle-punched reinforcements for composites. Consequently, this paper contains a detailed outline of the current state of 3D needle-punched technology for manufacturing advanced composite preforms. Properties of 3D needle-punched composites and some of the predictive models available for determining these properties are also reviewed. To conclude, a number of current and potential applications of 3D needle-punched preforms for engineering composites are highlighted, and issues impeding the use of 3D needle-punched composites are also summarized.

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Contents

1. Introduction

The textile industry has developed the ability to produce net-shape/near-net-shape preforms by the use of three-dimensional (3D) forming techniques, such as stitching, weaving, braiding, knitting and needle-punching [1]. In view of the potential for material savings and enhanced mechanical performance, these traditional textile technologies have been adopted for manufacturing fabric reinforcement for advanced composites [1–6]. However, for stitching, weaving, braiding and knitting, as is the case for manufacturing a fully fashioned preform, traditional textile technologies can prove time consuming and still be economically inefficient overall [1]. In particular, as compared to the above techniques, 3D needle-punching technology has not only overcome the shortcomings of two-dimensional (2D) laminates [6,7] but also overcome the process complexity and high cost disadvantage of other 3D preform manufacturing techniques. Table 1 summarizes the advantages

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Table 1
Advantages and disadvantages of 3D needle-punching and other 3D textile techniques [1,7,12,114].

3D techniques	Automation/cost	Advantages and disadvantages of 3D needle-punching and other 3D textile techniques
Weaving	Medium/ medium	3D weaving can produce complex near-net-shape preforms; 3D woven composites with a complex shape can be less expensive and simpler to manufacture; 3D weaving can tailor the through-thickness properties for a particular application; 3D woven composites have higher delamination resistance, ballistic damage resistance and impact damage tolerance; 3D woven composites can have higher tensile strain-to-failure values; 3D woven composites have higher interlaminar fracture toughness properties Difficult and expensive to manufacture quasi-isotropic 3D woven composites; 3D woven composites generally have lower tension, compression, shear and torsion properties; validated methods are not available for predicting long-term durability of 3D woven composites; predictive models for determining strength and fatigue performance have not been fully developed
Braiding	Low/high	3D braiding has the ability to produce complex near-net-shape preforms; 3D braided composites have higher delamination resistance and impact damage tolerance; 3D braided composites have greatly superior crashworthiness properties; 3D braided composites are less sensitive to notches Almost all 3D braiding machines are still under development, most 3D braiding machines are only capable of producing narrow preforms; stiffness and strength of 3D braided composites are generally lower than 2D laminates; predictive models for determining strength and fatigue performance have not been fully developed; durability and long-term environmental ageing tests on 3D braided composites have not been fully performed
Knitting	Medium/ medium	3D knitted preforms have better formability because they are more drapable; 3D knitting can produce more complex near-net-shape preforms; some types of 3D knitting can be done on existing automatic machines with little modification; some types of 3D knitted composites have higher impact damage tolerance and energy absorption (crash) properties Many 3D knitting machines are still under development; most conventional knitting machines cannot make thick preforms; weft knitting of non-crimp fabrics causes breakages and distortions to the in-plane fibres; 3D knitted composites generally have lower stiffness and strength properties; knitted composite components usually contain 'soft spots' and 'hard spots' caused by a change in the knit structure due to stretching of the fabric during preforming; predictive models for determining strength and fatigue performance have not been fully developed
Stitching	Medium/ medium	Can be inexpensive and simple to manufacture; improved handling of preforms (plies prevented from moving); improved impact damage tolerance, particularly to barely visible impact damage; improved delamination resistance to ballistic impact and blast loading; improved modes I and II interlaminar fracture toughness; improved interlaminar fatigue resistance; improved joint strength under monotonic and cyclic loading; slight improvement in through-thickness tensile modulus and strength Most sewing machines cannot stitch large and thick composite structures; most sewing machines require access to both sides of the preform; most sewing machines cannot stitch curved composite structures with a complex shape; stitching usually degrades the in-plane mechanical properties; the environmental ageing and durability of stitched composites is not fully understood; predictive models for determining strength and fatigue performance have not been satisfactorily developed
Needle-punching	High/low	3D needle-punching can produce complex net-shape/near-net-shape preforms; 3D needle-punched composites with a complex shape can be inexpensive and simpler to manufacture; 3D needle-punching can tailor the through-thickness properties for a particular application; 3D needle-punched composites have higher delamination resistance; 3D needle-punched composites have higher interlaminar fracture toughness properties; 3D needle-punched composites have higher interlaminar impact damage tolerance 3D needle-punching usually degrades the in-plane mechanical properties; the effects of high speed needle-punching process and multiple needle-punching process on properties are not fully understood; durability and long-term environmental ageing tests on 3D needle-punched composites have not been fully performed; predictive models for determining strength and fatigue performance have not been fully developed

and disadvantages of 3D composites made by weaving, braiding, knitting, stitching, and needle-punching separately, and it shows that 3D needle-punching is a versatile and highly automated preform fabrication technology, which is well suited to the rapid manufacture of components with complex shapes. Furthermore, 3D needle-punched composites have been largely successful in many structural applications, and these structural applications mostly focus on ceramic based and C based. 3D needle-punched carbon/carbon (C/C) and carbon/silicon carbide (C/SiC) composites, for instance, have been widely used in Airbus airplane C/C brakes, automobile brake disc, solid rocket motors, nozzle throats, exit cones [8,11] etc. However, there is not a comprehensive review of 3D needle-punching for engineering composites.

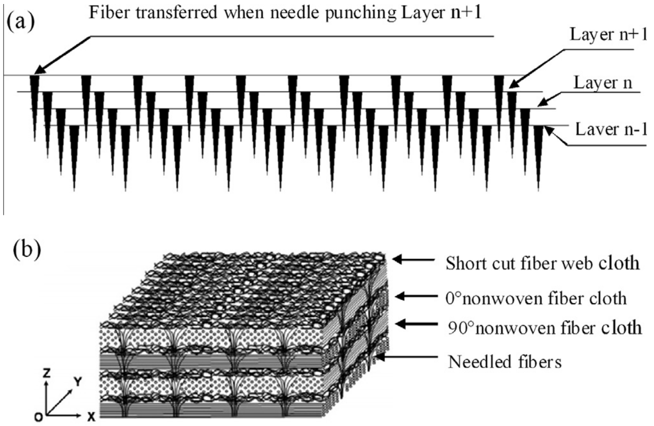

Fig. 1. (a) Generation of the 3D needle-punching process [8]; (b) schematic of a 3D needle-punching preform [90].

The aim of this paper is to provide readers with a general appreciation of the 3D needle-punching technology and the many opportunities it provides for producing efficient fiber preforms for advanced composites. With this objective, the paper firstly outlines the 3D needle-punching process and the structures of preforms and discusses the methods and machines for manufacturing preforms of different shapes. In this context, the performances of advanced 3D needle-punched composites with respect to mechanical properties, ablative properties, frictional properties and thermo-physical and electromagnetic properties are also reviewed. Theoretical and numerical models currently available for predicting the stiffness and strength of 3D needle-punched composites are presented. Finally, some current and potential applications of 3D needle-punching for engineering composites are highlighted. More importantly, issues impeding the use of 3D needle-punched composites are also summarized. With a comprehensive review of the subject, it is believed that textile engineers would be able to better understand the requirements

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