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Multiscale tool–fabric contact observation and analysis for composite fabric forming

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ABSTRACT

This paper provides measurements and analysis at the meso and microscopic scales of the real contact area between twill carbon fabric and a flat glass counterface. The mesoscopic contact area associated with tow contacts is about 55–75% of the nominal area. However, the total real contact length within the tow contacts, associated with microscopic contact at the fibre level, is only 4–8% of the idealised contact conditions with parallel touching fibres, for a nominal contact pressure of around 2 kPa. The dependence of real contact area on fabric shear angle is also investigated. The estimated real contact pressure is 15,000 times higher than the nominal contact pressure. Models or experiments of friction in composites forming which do not take into account the real contact situation, which is very far from an idealised packing arrangement, may fail to capture the essential tribological mechanisms.

1. Introduction

Shear is the main deformation mechanism in textile forming, independently of forming process and fabric type [1–3]. As a textile is formed into a curved shape, the shear angle varies locally over the part, reaching a maximum shear angle of up to 60° [4]. This is the case for dry or pre-impregnated woven and non-crimp fabrics with any type of polymer binder. In many composite forming processes, internal shear deformation occurs in conjunction with a compression load applied by a metal or rubber tool, which is used either to give the composite part the desired shape before filling it with resin or to reduce the voids between already-impregnated prepregs. As well as internal fabric shear, there may be gross sliding between the tool and fabric and between plies in a multi-ply stack, with details depending on the composite architecture and processing method. During the forming process, friction between the composite ply and the tool, and between composite plies, may play an important role in shaping the part and may also affect the formation of local defects such as wrinkling in the composite part.

Textile shear behaviour at the macro and mesoscopic scales is usually investigated either by bias extension or picture frame tests [5–10]. Shear characteristics obtained by these tests or by virtual experiments [11,12] are used in textile forming simulations. Most of the numerical modelling work presents the fabric either as a macroscopic deformable solid without details of the internal structure, or as a set of woven tows defined at the mesoscopic scale [13–19]. There are only a few numerical models which regard composite fabric as composed of individual fibres at the microscale [20,21]. Due to the computational cost, the tows contain only a relatively few fibres, far from the situation of real fabrics with thousands of fibres in a tow. Mesoscopic models seem the most promising approach, as they represent a compromise between the time of computation and the accuracy of representation of internal deformation. The mesoscopic contact area between tows and a tool is one of the results provided by such models. At this scale, each tow/tool contact spot is of the order of tens of square millimetres, and the total ply/tool contact area is composed of many of these mesoscopic contact spots. It is generally assumed that, since each tow is densely packed with fibres, each mesoscopic contact spot is fully filled with fibre micro-contacts [11,13,16,29,33,38–40]. However, to our knowledge, this hypothesis has not been verified. The experimental work presented in the current paper enables verification of whether this widely accepted hypothesis is correct and, therefore, will contribute to the further improvement in accuracy of composite forming simulations.

A number of experiments have been done to measure friction between fabric and a metal tool [22–31]. The friction force is usually measured while sliding a large piece of fabric against a metal

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counterface, and the friction coefficient is defined for the whole apparent contact surface. This approach does not represent composite forming accurately for two reasons. Firstly, there is an ambiguity associated with the ply/tool friction term. While the friction force measured in these experiments is due to sliding friction between two macroscopic continuous solids, in real forming of curved composite parts most of the frictional energy is dissipated by local ply/tool friction due to shear. The former friction type is characteristic for the fabric/blank holder relationship. By contrast, the latter friction type is relevant for the moulded area which undergoes high shear deformation under the compression force applied by the tool. This latter type of friction is very different from the fabric/tool sliding friction and needs to be understood to model accurately forming of these materials.

Secondly, in order to understand and to model friction-related phenomena accurately, ply/tool contact should be investigated at the microscopic level. The understanding gained from such an approach can also inform design and characterisation of appropriate experiments. As far as we know, the real contact area in fabric/tool contact has not previously been measured. The real contact area between solids is often much smaller than the apparent one and depends on the surface topography, material and normal load. For instance, the ratio between real and apparent contact areas for metal/metal contact is typically about 0.5×10^{-6} under a normal pressure of 1.4 kPa [32]. On the other hand, for the contact of two elastomers, this ratio can be close to 1. Recently, a contact model for fabric/tool friction was introduced [33], which looks at the influence of roughness on the metal tool on friction in fabric forming. Considering contact at the mesoscopic level, this model uses an assumption of an idealised packing of parallel touching fibres within each tow/tool contact spot. However, this critical assumption has not been verified. Moreover, high shear deformation of fabrics during forming induces dramatic surface changes, as seen by the naked eye and through microscope observation [34,35]. Does the real contact area and local friction change during shear due to these mesoscopic tow deformations?

In this paper, we will present a methodology to investigate microscopic fabric/tool contact under shear loading, and apply this to the forming of twill fabric. The aim of this study is to bridge the gap between modelling of fabric forming and real forming processes and to provide experimental data of real contact area in fabric forming that can be used in modelling simulations. To do so, we use a novel experimental rig and method described in detail in Ref. [36]. In particular, Ref. [36] presents an analysis of the deformations and forces applied by the experimental rig, discusses the similarities and differences of this method comparing to the classical shear experiments, and describes an image analysis algorithm used to extract the images of fibre contact. The focus of the current paper is to take this method for identifying contacting fibres and use this in a multiscale analysis of composite fabric/tool contact under shear loading.

This paper studies tool/fabric contact of dry twill carbon fabric, representing the pre-forming step for a resin transfer moulding process. The contact pressure used here is of the order of real forming pressures applied to the fabric in a highly deforming area, where shear takes place during the pre-forming process. The method presented works for contact between a glass plate and carbon fibres and can be used for any carbon fibre composite architecture (UD, fabric, NCF, 3D...). Moreover, wet contact of carbon fabric impregnated with polymer matrix can also be studied by the method presented. In principle, a contact with other optically reflective fibres can be measured using the same technique if the optical properties and thickness of the semi-reflective coating are adjusted. The use of glass as a counterface is imposed by the combination of transparency and hardness of this media. Curvature of the glass plate could be introduced to simulate a curved mould, but this would require correction of the associated contact image distortion.

2. Materials & methods

2.1. Experimental method

This paper uses a micromechanical experimental rig which has been developed to investigate composite forming behaviour at the microscopic scale. The details of the rig and the methods used to identify individual fibre contacts are given in [36], and here we give a brief overview. The loading rig is illustrated in Fig. 1. A key feature of the rig is the ability to observe the evolution of microscopic contacts under simultaneous application of shear and compression loadings. A composite fabric sample of size $80 \times 80\,\text{mm}^2$ is compressed via a screw-spring arrangement between two glass plates with a gauge area of $45 \times 20\,\text{mm}^2$. Two linear motors pull the fabric in opposite directions at ±45° to the tow orientations, thereby increasing the shear angle between crossing tows. An open shear frame is used to clamp the specimen and connect it to the motors. The rig is placed under an optical microscope equipped with a camera.

A semi-reflective optical coating was deposited on one of the glass plates to enable direct contact observations. Such a coating is often used in tribological experiments to measure the thickness of lubrication films in ball/disc sliding contacts. The optical film has two layers, a base layer of chromium and a top layer of silica in contact with the fabric sample. The thicknesses of both layers (140 nm for the SiO_2 and 8 nm for the Cr) were optimised for our application in order to obtain the best contrast of carbon fibre contacts. A Matlab algorithm to analyse the obtained images and detect fibre contacts was developed and described in Ref. [36]. In brief this uses a combination of filtering and thresholding to identify bright, elongated features corresponding to the fibre contacts. The algorithm scans an image which contains clearly visible bright contact areas and detect lines corresponding to fibre contacts. There is insufficient image resolution to measure accurately the width of individual fibre contacts, so only the length of the fibre contacts is measured by the algorithm, enabling a calculation of the total contact length in the image. Because of the clear contrast produced by the optical film, identification of contacts is a relatively straightforward and unambiguous process. Several coated

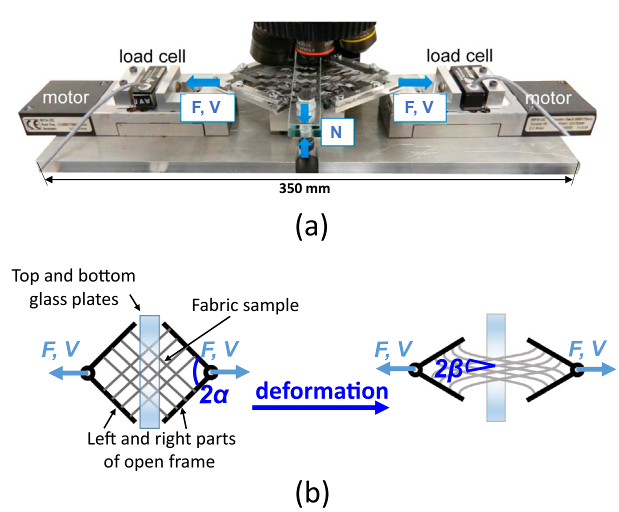

Fig. 1. Experimental rig: (a) photograph; (b) deformation schema.