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Tribological behaviour of multilayered textile composites: The effect of reciprocating sliding frequency

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ABSTRACT

Textile composites have been used for various applications because of their enhanced strength/weight ratio and versatile properties compared to other materials such as metals. Many studies have investigated the tribological behaviour of textile composites, but none have focused on the tribological characterization of 3D multilayered woven reinforced textile composites. Five types of 3-ply woven interlocked structures with varying interlacements were used as reinforcement for the nylon fibre/polyester resin composites for the present study. The influence of the textile structure interlacement on the tribological properties of the composite material (in terms of wear volume) was investigated in this work. Further, special attention was given to understand the effect of sliding frequency on the tribological behaviour and driving wear mechanisms. The tests were conducted on a new class of reciprocating sliding wear tester, in dry (unlubricated) conditions, under a fixed applied load of 20 N by varying the frequency of oscillating motion ($0.5 \leq f \leq 8$ Hz). In addition, tests were also conducted, at a constant frequency of 4 Hz and as a function of several loads (5 N to 40 N). From these tests, a 3-ply woven reinforced composite with the best tribological performance as a function of frequency and load was identified. It was observed that the type of woven structure had an influence on the tribological properties. Therefore, the selection of a textile composite should be based on the load and frequency at the service condition. The wear mechanisms involved in the tribological process were also analysed.

1. Introduction

Textile reinforced composites are a major type of composite materials used widely for aerospace, naval, defence, automobile and civil applications. Fibre reinforced composites are used not only for their structural properties, but also for electrical, thermal, tribological, chemical and environmental purposes for a variety of industrial applications [1]. It is important to characterize the tribological behaviour of such composites as they are employed in a broad a range of applications where friction and wear phenomena are also involved.

During last few years, several studies have reported the tribological behaviour of textile polymer composites [2–13]. Significant progress was made by Nak-Ho and Suh [2] and Lee et al. [3] on the friction and wear behaviour of textile polymer composites as a function of varying fibre orientations with respect to the sliding direction. The former observed for graphite fibre-epoxy composites that both wear and friction coefficients were low when the orientation of the fibres was normal to the sliding surface. In Kevlar-epoxy composites when the fibres were oriented normal to the surface and the sliding direction, the wear volume loss was also low but the friction coefficient was the highest [3]. Shangguan and Cheng [4] studied the tribological properties of lanthanum treated carbon fibres reinforced PTFE composite under dry sliding conditions as a function of frequency. In detailed study of the effect of fibre orientation on the wear behaviour of carbon-polyether ether ketone (PEEK) and Kevlar-epoxy laminates [5], it was shown that the wear rate did not significantly change for fibre orientation variations of up to 30° from the normal orientation. An important influential factor was whether the abrasive material compressed the fibre or tended to pull the fibre out from the composite as it passed. The latter mechanism of fibre pull-out generated a higher wear rate.

In an interesting study of glass fibre reinforced poly(vinyl)-butyral-modified phenolic composites, comparison between wear performance of woven roving, plain weave and satin weave fabric reinforcement geometries has been carried out. It was observed that the fabric geometry had a significant influence on the friction and wear behaviour of the composites [6]. The wear rate was low-

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Nomenclature

c	contact field
i	interlacing field
f	float field
I	Interlacement Index
i_{wp}	interlacements in warp
i_{wf}	interlacements in weft
R_1 and R_2	warp and weft repeat of woven design
V_f	fibre volume fraction of the composite
W_f	weight of fabric (g/m^2)
W_c	weight of composite (g/m^2)
N3P1, N3P2, N3P3, N3P4, N3P5	The 3-ply multilayer fabric samples

Greek letters

σ_c	composite density
σ_f	fibre density

est for the plain weave glass fabric composite, while the woven roving composite exhibited greater tensile, flexural, impact and interlaminar shear strengths. Yoshioka and Seferis [7] performed tension fatigue tests of resin transfer moulded woven carbon fabric composites. They recommended a model to predict the modulus deterioration under tensile fatigue damage conditions based on a combination of the crimp model and the shear-lag model. Tsang et al. [8] reported fatigue properties of vibration-welded nylon 6 and nylon 66 reinforced with glass fibres. In general, low weld pressure appeared to give better fatigue performance than high weld pressure in vibration-welded nylons. In the absence of hysteretic heating, fatigue cracks initiated in the weld material. Fibre debonding and matrix micro-cracking lead to fatigue crack propagation and fast fracture under cyclic loading [9]. Recently, the same authors of the current study [10] have conducted an elaborative study of the tribological behaviour of textile warp-knit woven polymer composites as a function of applied load and sliding distance in dry and lubricated contact conditions. Textile polymer composites with different orientations and resins were considered for dry and lubricated contact conditions. It was found that a composite biaxial warp-knit reinforced with epoxy resin was the most suitable for tribological applications. Further, many other interesting works were reported on the tribological process of the textile composites and acting wear mechanisms [11–13].

Most textile composites have been made by stacking layers of woven preforms leading to prominent delamination failure under performance/application conditions [14]. Multilayer interlocked fabrics are a specific class of preforms, which can also fulfil the requirements for damage resistant composites, but have been scantily explored to achieve interlocking of fabric layers during the weaving stage [15–17]. The manufacturing of preforms of interlocking fabrics is advantageous because they are cost effective and the manufacturer has control over layer interlocking density based on weave variations apart from imparting higher impact and delamination resistance to the fibre reinforced composites. So, an attempt was made to study the effect of a multilayer structure on the sliding wear behaviour by developing five different multilayer interlocked woven structures with varying interlacements for composite reinforcement applications.

There are no specific studies reported, till today, on the tribological response of textile composites as a function of sliding frequencies. However, from the practical point of view, such aspects are very significant as the composites are exposed to varying sliding frequencies when used, for example, for ship structure and aerospace applications. This study investigated the effect of sliding frequency

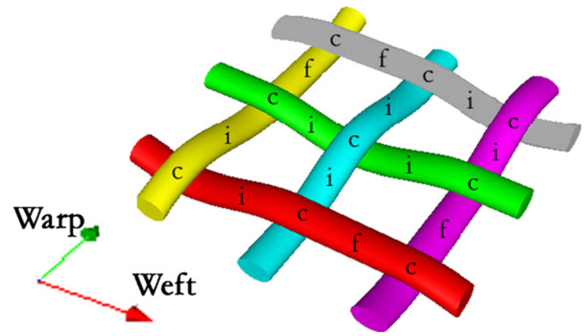

Fig. 1. Fabric fields.

on the tribological behaviour of multilayered textile composites using a new class of reciprocating sliding tribometer in dry (unlubricated) conditions. The main objectives were to understand the dominant wear mechanisms as they related to the oscillating motion and frequency for dry sliding conditions and to determine which of five composites had the best tribological behaviour.

2. Materials and methods

2.1. Textile polymer composites: woven preforms and Interlacement Index (I)

Woven preforms have two sets of yarns (warp and weft, Fig. 1) perpendicular to each other that are interlaced by a weaving process. Division of woven fabric area to three types of fields has been suggested by Selivanov, in a Russian journal, reviewed and reported by Milasius et al. [18]. The field types are defined as contact (c), interlacing (i) and float fields (f) (Fig. 1). A contact field is defined as the projected region occupied by both warp and weft thread systems. An interlacement field is the region between two contact fields where there is cross-over of warp yarn from one plane to another because of weaving around a weft yarn, and vice versa. When the yarn between two contact fields does not shift from one plane to another it is termed as float field.

One study generalized the structure-property correlation of the woven structure using an integrated factor based on interlacements [19]. The factor is known as the Interlacement Index (I) and is defined by Eq. (1). The Interlacement Index is the ratio of the number of interlacement fields in any given weave repeat to the maximum possible number of contact fields in the design, where i_{wp} and i_{wf} are interlacements in warp and weft, respectively. The product of warp and weft repeat ($R_1 \times R_2$) of a woven design is equal to the maximum possible number of contact fields in the woven design repeat. The highest interlacement is seen for plain woven structures ($I = 2$) and non-interlaced structures would have an I value of zero.

$$I = \left(\frac{i_{wp} + i_{wf}}{R_1 R_2}\right) \tag{1}$$

The influence of structural variations on the wear behaviour of composites has been investigated for plain and satin structures [20], but investigations of the tribological properties of multilayered textile composites with respect to structural factors such as the Interlacement Index have not yet been performed.

2.2. Multilayer woven preforms

The 3-ply multilayer fabric samples were woven on a four harness flexible rapier automatic loom (Dornier), at 400 rpm with 24 ends/cm and 12 picks/cm settings. Five meter lengths of five varieties of nylon 3-ply fabrics (N3P1–5) were woven using high