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Towards an advanced modeling of failure mechanisms' interaction in fiber-reinforced polyester: A mixed-mode loading concept

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ABSTRACT

This attempt proposes a Finite Element Approach (FEA) to investigate the tribological behavior of glass fiber reinforced polyester composite. The 3D finite element model was developed upon ABAQUS/Explicit. The Johnson-Cook criteria were considered for describing the material behavior and damage of both fiber and matrix phases. The fiber/matrix interface behavior was, however, modeled using a thin cohesive zone (CZ). A mixed-mode loading concept was specially adopted to predict delamination propagation within the interface. The prevailing wear mechanisms owing to Multi-Scratch Test (MST) were inspected at variable load and attack angle, using scanning electron microscope (SEM). Wear maps were built to highlight the correlation between friction coefficient and wear mechanisms. Predictions of both elementary and interacting mechanisms showed excellent correlation with observations. It was revealed that material removal process varies sensitively with the dominating failure mode. The proposed approach exhibits good ability not only in predicting active mechanisms but also in detecting damage sequences governing the surface integrity during scratching.

1. Introduction

The composite materials have become increasingly popular in several industrial sectors such as astronautics, aeronautics, and transports. In addition to their outstanding mechanical properties, the composite materials possess low densities. In several applications, the identification of their tribological behavior i.e. elementary wear mechanisms, friction, lubricant absorption rate, etc. still remain, however, challenging. The anisotropic nature of such materials makes it difficult both the experimental testing and the numerical modeling due to the interaction of elementary mechanisms and difficulty of controlling the interface behavior. The local analysis is mostly used to study the wear mechanisms evolution. In some attempts, the local approach analysis was used to investigate the tribological properties of each composite constituent separately. Scratch test is among the most known techniques used for characterizing tribological behavior of metals [1–3], polymers [4,5], and composites [6,7].

Kim et al. [8] studied the effect of fibers' rate and direction on friction, and wear of short glass fibers reinforced polyamide (PA12) by using a block-on-ring tribotester. They demonstrated that the composite wear rate decreases with the increase of the fibers' amount. A better wear resistance was detected with a composite containing 30 wt% of glass fiber. They also proved the sensitivity of tribological behavior of the composite to temperature and fiber amount.

Using pin-on-disk test, Quintelier et al. [9] investigated the wear mechanisms in glass fiber reinforced polyester (GFRP) composites at dry sliding conditions. They proved that the initial fibers' breakage is always occurring in a cross section regardless of the fiber orientation. In the case of sliding perpendicular to fiber orientation, the initial fiber fracture was attributed to bending causing longitudinal strains. When the fiber orientation is parallel to the sliding direction, high stresses are found to be responsible of the shearing forces. According to the SEM observations, typical composite wear mechanisms, i.e. fiber breaking, fiber/matrix interface debonding, matrix fracture, and fiber pullout, were highlighted.

Wear maps were commonly used in open literature to achieve a better correlation between the tribological parameters and the wear mechanisms [10–12]. Using this analysis technique, Briscoe et al. [13] demonstrated the sensitivity of wear mechanisms to the conical indenter angle and the cure temperature owing to GFRP scratch test. For low angles, it was shown that ductile or

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viscoelastic-plastic ploughing switch to a brittle fracture when increasing the cure temperature.

While the experimental approaches, namely, the scratch tests, achieved good conclusions on the single-phase material behavior, i.e. metals, polymers, etc. [14–17], they showed some limitations in accessing all the sought details and local mechanisms dominating the composite material behavior. In particular, the multiplicity of mechanisms acting alone or in complex an uncontrolled interaction makes these approaches not sufficient enough to fully understand the tribological behavior of fiber reinforced polymer composites. However, the finite element analysis (FEA) offers an appreciable alternative because of good modeling flexibility, significant time saving, and high solution accuracy.

Since more than a decade, Goda et al. [18] have developed a micromechanical model for studying the tribological behavior of unidirectional composites using steel asperity-to-composite pair sliding model while sliding was performed perpendicular to fiber orientation. The proposed micro/macro FE approach basing in the modeling of fiber/matrix interface shows much better ability in predicting wear mechanisms than the equivalent macro mechanical approaches widely used in literature [19,20]. According to the predictions, it was revealed that the matrix breaking is due to high shear stress, followed by the formation of a thin film of wear debris. However, the backward fibers' edges in the contacting zone may also crack under high normal stresses. In addition to the prediction of the whole wear mechanisms observed experimentally, the histories of local modes such as matrix shear failure, fiber/matrix debonding, fiber cracking, etc. were successfully highlighted.

Friedrich et al. [21] simulated the sliding of a spherical indenter against GFRP composite sample. When sliding parallel to fiber orientation, it was revealed that fiber/matrix debonding, matrix shearing, and fiber thinning are dominating the wear mechanisms whereas fibers' cracking mechanisms acts in addition to the aforementioned wear modes when sliding perpendicular to fiber orientation. Confrontation of predictions to observations performed on samples scratched by diamond tip proved the validity of simulations.

In spite of appreciable researches have been developed for investigating wear in composite materials, most of them still focused on the SST and neglect, in turn, the effects of physical interactions between active mechanisms that might potentially be of important role in governing local behavior at surface and subsurface.

This paper aims at emphasizing the correlation between tribological parameters and wear mechanisms' interactions basing on micromechanical modeling. Scratch maps were built to highlight the dominating mechanisms and to appreciate the reliability of the numerical predictions.

2. Experimental procedure

2.1. Sample preparation

The sample used in the design of experiments is made of GFRP composite. The material was supplied (supplier: Qinhuangdao Shengze New Material Technology Co., Ltd.) as pultruded rectangular section panels of $1000 \times 50 \times 6\ mm^3$ in dimensions. The test specimens were cut at room temperature, under lubrication, at size $50 \times 50 \times 6\ mm^3$, using an Al_2O_3 abrasive grain wheel (Type: PRESI A0) of $\varnothing 230 \times 1.6$ mm in dimensions. The composite material consists of unidirectional E-glass fiber with an average diameter of 23 μm and 21 wt%. The considered composite is, besides, filled with 14 wt% clay filler (ASP400). The scratch tests were performed upon $50 \times 50\ mm^2$ sample face.

2.2. Scratch tests

Scratch tests were performed using the device whose technical specifications were presented in [22,23]. The testing set up allows varying the different test parameters, namely, the attack angle, the normal load, the scratch velocity and length. A conical uncoated HSS indenter made of W18Cr4V, treated to be at 64 HRC in hardness, was considered for performing the scratch tests [24]. The system ensures the sample target face to be normal to the indenter. Here, both the scratch velocity and length are fixed at $210\ mm\ min^{-1}$, and 30 mm, respectively. However, the normal load and the attack angle are taken ranging in 10–50 N, and 10°–60°, respectively. During the test, the tangential load was recorded using piezoelectric transducer connected to an acquisition system. All tests were repeated three times in dry environment and room temperature. In order to appreciate the role of tribological mechanisms' interaction, Multi-Scratch Test (MST) using three aligned indenters with fixed separation distance was confronted to single scratch test (SST). In MST, the equivalent normal load was ensured by three dead weights fixed separately on the indenters. The inter-indenter distance B was kept constant at 1 mm while scratching length was fixed to 30 mm. The apparent friction coefficient (μ_{app}) was calculated referring to Coulomb's law. The wear mechanisms in the two test types were inspected using scanning electronic microscope (SEM).

3. FE modeling

3.1. Assumptions, mesh construction, and B.Cs.

The FE model was developed upon ABAQUS/Explicit code using dynamic/explicit integration scheme. The matrix and the fiber were modeled as separated phases. For predicting debonding mechanisms, the fiber/matrix interface was intentionally modeled by a cohesive zone of 2 μm in thickness [25]. At the difference of literature considering random arrangements [26,27], periodic regular arrangement [28] was assumed herein for building the geometrical composite plate in order to properly control the volume fraction of fibers and to avoid mesh problems. The fibers have hexagonal regular arrangement, average diameter of 23 μm as experimentally inspected by optical microscope, and volume fraction of 34%. Fig. 1a shows the geometry, boundary conditions, and mesh constructions adopted for SST.

In the proposed model, only the zone of interest (ZOI) was simulated using a rectangular parallelepiped of $187 \times 200 \times 800\ \mu m^3$. The upper region where indenter-material contact occurs during scratching, was modeled as multi-phases' material (MPHM) composed of fiber, matrix, and interface phases. Out of the ZOI, the composite was modeled basing on equivalent orthotropic homogeneous material (EOHM) assumption. A total of 20 fibers were used to build the micromechanical sections in SST and MST, respectively. A 3D mesh was generated using the test plate dimensions, where more than 468,142 nodes and a total of 162,948 solid continuum brick elements (type: C3D8R) and 171,828 prism elements (type: C3D6) with linear interpolation between nodes, were used. The mesh discretization was intentionally refined in the vicinity of the indenter at ZOI.

As for SST, only the ZOI was investigated in MST (Fig. 1b) by the reason of rapid convergence. The composite plate was modeled by $2B \times 200 \times 413\ \mu m^3$ parallelepiped, where B is the indenters' separation distance. In order to highlight the effect of interaction, a total of 44 fibers and interfaces were used for building the MPHM section. The model consists of 364,284 nodes connecting 140,980 solid continuum elements (type: C3D8R) and 175,801 prism elements (type: C3D6).