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# Quantitative characterization of the fiber orientation variation in the Csf/Mg composites

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ABSTRACT

Based on the principal strain driven fiber orientation evolution mechanism, the fiber orientation variation factor **V**, which is a function of the principal strains, is proposed to quantitatively characterize the variation of fiber orientation angles in the extruded Csf/Mg composites. The FE analyses are implemented to numerically simulate the extrusion forming process of Csf/Mg composites. The fiber orientation variation factors predicted by the FE simulations are compared against those measured from the micrographs of the extrusion experiments of Csf/Mg composites. The results show that the fiber orientation variation factor **V** of the FE simulations and of the extrusion experiments match well such that the fiber orientation variation factor **V** is valid and convenient to characterize the fiber orientation variation in the extruded Csf/Mg composites. The distribution of the fiber orientation variation factors illustrates that the fibers in the extruded Csf/Mg composites are reoriented towards the direction of the maximum principal strain, and deviated from the directions of the medium and minimum principal strains.



## 1. Introduction

As a set of the typical advanced materials, short fibers reinforced composites have the huge potential applications in the automotive, aviation, aerospace, national defense industries and sports market, etc., [1–4], because of their excellent mechanical and physical properties. It has sustained a vigorous scientific and technological interest in the area of their effective mechanical properties [3,5–7], which not only depend on the fiber volume fraction [8–10] and the interfacial adhesion between the fiber and matrix, besides the mechanical properties of the fibers and matrix [7,11–14], but the fiber orientation [15,16]. Therefore, it is important to investigate the fiber orientation in the Csf/Mg composites.

Attention on the fiber orientation of composites are mainly focused on two aspects: the effect of the fiber orientation on the mechanical properties of composites, and the fiber orientation evolution in the primary or further forming process of composites. There have been many researches on the effect of the fiber orientation on the mechanical and physical properties of composites last decades [15–18], which will not be investigated here, however. In this article, the fiber orientation evolution in the extruded Csf/Mg composites is emphasized.

The fiber orientation evolution in the short-fiber reinforced composites has received the considerable attention in the literatures. Hieber and Shen [19] proposed the generalized Hele–Shaw approximation to calculate the velocity field, which were then used to determine the fiber orientation, using the scheme developed by Advani and Tucker [20] and Bay and Tucker [21]. The Folgar–Tucker (FT) model [22] was used for the prediction of the fiber orientation in injection molded parts, with varying degrees of success. In a recent work [23] of authors the principal strains driven fiber orientation evolution mechanism which stated that the orientation evolution of fibers was determined by the principal strains, was proposed to predict the fiber orientation evolution in the extruded Csf/Mg composites.

In the work of Bay and Tucker [21], a unit vector **P** parallel to the axis of fiber was introduced to represent the fiber orientation, which was expressed by the Eulerian angle $\theta$ and $\phi$. And then the expression of the Eulerian angle was developed by proposing a probability distribution function $\psi(\theta,\varphi)$ [21]. The probability orientation distribution function gave a complete description of the fiber orientation, and was widely used to express the fiber orientation. However, because of the complex computation of the probability distribution function, the orientation tensor [20] was proposed to express the fiber orientation.

In this article, the emphasis is on the characterization of the fiber orientation variation so that the fiber orientation variation factor **V** is proposed and developed, which is a function of the

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principal strains. Based on the principal strains driven fiber orientation evolution mechanism, the fiber orientation variation in the extruded Csf/Mg composites is quantitatively characterized. In two simulation examples, the fiber orientation variation factors predicted by the FE simulations are compared against those measured from the micrographs of the extrusion experiments of Csf/Mg composites to verify the validation and convenience of the fiber orientation variation factor **V**. And according to the contours of the fiber orientation variation factors, the fiber orientation variation in the extruded Csf/Mg composites is analyzed.

## 2. Quantitative characterization of the fiber orientation variation

When Csf/Mg composites are extruded, the short carbon fibers translate and rotate with the matrix deforming and the fiber orientation changes. Regarding to the representation of the fiber orientation, the most commonly used expressions are the probability distribution function $\psi(\theta, \varphi)$ [21] and the fiber orientation tensor [20]. Ref. [23] proposed the fiber orientation factor **F** to characterize the fiber orientation distribution in the Csf/Mg composites.

In this article, the principal strain driven fiber orientation mechanism [23] is used to determine the fiber orientation evolution in the extruded Csf/Mg composites and a new expression i.e. the fiber orientation variation factor **V** to characterize the fiber orientation variation in the extruded Csf/Mg composites is proposed. The fiber orientation variation factor **V** represents the variation between the initial fiber orientation angle in the Csf/Mg composites without deformation and the final fiber orientation angle in the Csf/Mg composites with a large deformation. And its three components $V_1, V_2$ and $V_3$ represent the fiber orientation variation in the directions of the maximum, medium and minimum principal strains, respectively.

Here, some hypotheses are made on the derivation of the fiber orientation variation factor **V**.

(1) No separation between the fibers and matrix of Csf/Mg composites.
During Csf/Mg composites are extruded, short carbon fibers are strongly constrained by the surrounding magnesium alloy matrix. Assuming that there exists a perfect bonding between the fibers and matrix of Csf/Mg composites, i.e. the fibers does not rotate and translate relative to the surrounding matrix, the positions and orientation of fibers completely depend on the deformation of the matrix.

(2) No bending deformation of the fibers.
The microstructures of the extruded Csf/Mg composites are shown in Fig. 1, in which short carbon fibers without significantly bend can be found.
Generally, the size of a single short fiber is much smaller than that of the composites. During the composites deform, the strain gradient of one point or particle in the composites is, however, very small. Therefore, it can be approximated that the short fibers are surrounded by the matrix with a constant strain.

(3) No translation and rotation interference between the fibers.
It is obvious that there exists no translation and rotation interference between the fibers in the short carbon fibers preform and Csf/Mg composites without deformation. The fiber volume fraction of Csf/Mg composites is relatively small (about 10%) such that there exists no significant translation and rotation interference between the fibers when Csf/Mg composites have a large deformation.

(4) No fiber damage and fracture.
When Csf/Mg composites are extruded, some fibers might damage and fracture because of bearing the stress which is beyond the yield stress. However, the damage and fracture of fibers in the extruded Csf/Mg composites are neglected, and fibers will always keep their complete shape during the deformation of Csf/Mg composites.

(5) Totally random initial fiber orientation distribution.
The preparation processes of the short carbon fibers preform and Csf/Mg composites determine the initial fiber orientation [24–26]. The short carbon fibers preforms with porous structure are shaped by wet forming process [27]. The microstructures of the short carbon fiber preforms (as shown in Fig. 2) illustrate that short carbon fibers are distributed approximately randomly.
The vacuum pressure infiltration process [28] is used for fabricating Csf/Mg composites. During the infiltration and solidification of the liquid magnesium alloy under the pressure, the preform sustained the vertical pressure, which would result to the deformation of preform. However, experiments show that the deformation of short carbon fibers preform is relatively small so that this deformation can be ignored. Therefore, the initial fiber orientation of Csf/Mg composites primarily depends on the preparation processes of the short carbon fibers preform, which means that the short carbon fibers are randomly distributed.

## 3. Governing equations of the fiber orientation variation factor

Given that point $O$ is a random point in the Csf/Mg composites, a local Cartesian coordinate system $o-xyz$ is established. In the coordinate system $o-xyz$, the distribution of fibers is totally random. The fiber length is set to be $r$ in the Csf/Mg composites without deformation. Then we can obtain the orientation sphere and orientation ellipsoid as shown in Fig. 3.

The intercepts $a, b$ and $c$ of the orientation ellipsoid on the $x, y$ and $z$ axes take the form of the maximum principal strain $\varepsilon_1$, the medium principal strain $\varepsilon_2$, and the minimum principal strain $\varepsilon_3$ and can be written as

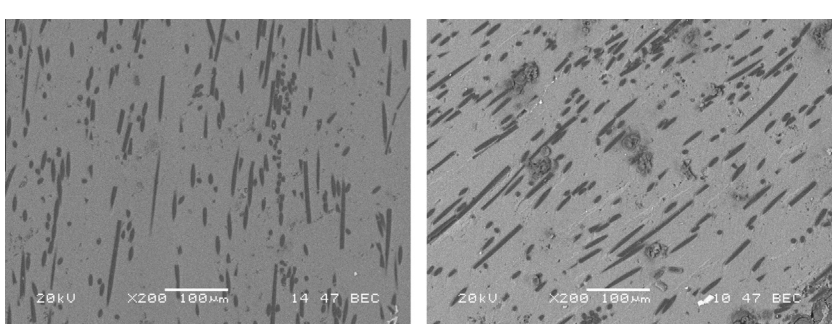


**Fig. 1.** Microstructures of the extruded Csf/Mg composites with a large deformation.