

Identification of True Stress-Strain Curve of Thermoplastic Polymers under Biaxial Tension

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ABSTRACT

This article is concerned with identification of true stress-strain curve under biaxial tension of thermoplastic polymers. A new type of biaxial tension attachment was embedded first in a universal material test machine, which is able to transform unidirectional loading of the test machine to biaxial loading on the specimen with constant velocity. Cruciform specimen geometry was optimized via FE modeling. Three methods of calculating true stress in biaxial tension tests were compared, based on incompressibility assumption, linear elastic theory and inverse engineering method, respectively. The inverse engineering method is more appropriate for thermoplastic polymers since it considers the practical volume change of the material during biaxial tension deformation. The strategy of data processing was established to obtain biaxial tension true stress-strain curves of different thermoplastic polymers.

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INTRODUCTION

With the increasing requirements of saving energy and reducing emission, there has been a rising interest from car manufacturers for using plastic materials in interior/exterior components and crash energy-absorbing parts (e.g. instrument panels, bumpers) in the last decades. Thermoplastic polymer is a category of commonly used plastics which is light-weight, inexpensive, easy-modeling, reusable, and sustainable. Characterization of the mechanical properties of thermoplastic polymers becomes indispensable in NVH and crashworthiness design of structures with CAE method. Although a number of previous studies have been carried out on characterization of mechanical properties, especially the yield behavior of plastics [1, 2, 3, 4], there are still no sufficient accurate test data under multiple-axial loading conditions.

The yielding behavior of thermoplastic polymers is usually pressure dependent and influenced by temperature and strain rate as well [5]. Yield criteria of isotropic polymers have been intensively studied as Ghorbel [6] reviewed in 2008. According to these criteria, it is impossible to obtain accurate yield surface of thermoplastic polymers merely with uniaxial tension stress-strain curve. Commonly used pressure-dependent yield criterion, e.g. Drucker-Prager criterion [2,3], requires both the first invariant and second invariant of the stress tensor. Consequently stress-strain curves under different stress states are required. While our previous study [7] has shown that yield surface determined via test data from uniaxial tension, compression and simple shear with least square fitting method is not necessarily

able to predict accurate yielding behavior under biaxial tension. In this sense, biaxial tension data is critical for constructing yielding surface of thermoplastic polymers.

On the other hand, regarding the in-service loading condition of some thin-walled panels, biaxial tension is one of the crucial stress states which has to be considered in the characterization of mechanical properties for thermoplastic polymers due to aforementioned pressure dependence. Despite the large demand, there is little reliable biaxial tension experimental data especially the stress-strain relationship after yielding. The main difficulties consist of two aspects. One is how to obtain ideal biaxial tension stress state of specimen in experiments. The other is how to calculate the true stress-strain curve under biaxial tension.

Corresponding to these two issues, the experimental techniques of biaxial tension are first investigated in the present paper, including design of biaxial tension system and optimization of cruciform specimen. Furthermore we focus on determining appropriate method to calculate true stress of biaxial tension, which helps the construction of yielding surface of thermoplastic polymers.

BIAXIAL TENSION TESTING

It is not easy to carry out ideal biaxial tension test for thermoplastic polymers due to large plastic deformation, strain localization, etc. Boehler et al. [8] classified four test techniques which have been used to produce stress states of biaxial tension.

1. Bending of specially shaped thin plates.
2. Hydraulic bulge test.
3. Thin-walled tubes subjected to tensile or compressive loads combined with torsion or internal/external pressure.
4. In-plane loads along perpendicular arms of cruciform specimen.

According to Ref. [8], among the four techniques, the last one is the most realistic experimental solution to biaxial tension test due to convenience of implementation. Hannon and Tiernan [9] presented a comprehensive review of the main biaxial test systems that have been developed based on cruciform specimen and classified them into two types: stand-alone biaxial testing machines and link mechanism attachments for biaxial testing. Kuwabara et al. [10] designed a servo-controlled hydraulic biaxial testing apparatus shown in Figure 1. Opposing hydraulic cylinders were connected to common hydraulic lines so that the same hydraulic pressure was applied to each other. To maintain the center of the specimen stationary throughout the test, a pantograph-type link mechanism was utilized. In an attempt to reduce the cost associated with building stand-alone test machines, link mechanism attachments were designed for biaxial testing. A biaxial test device shown in Figure 2 was developed at the Fraunhofer Institute in Germany by converting a compression tester by a series of linkages [11]. Ferron and Makinde [12] developed a mechanism of transforming unidirectional tension into a biaxial tension by using eight links, converting the vertical movement of the crosshead into bi-directional movements of the grippers, as shown in Figure 3.

According to previous studies, biaxial tension system should meet the following requirements:

1. Center of specimen keeps stationary under biaxial loading.
2. Displacement along opposite arms of the cruciform specimen should be equal to each other.
3. Loading speed should be as constant as possible throughout the test.

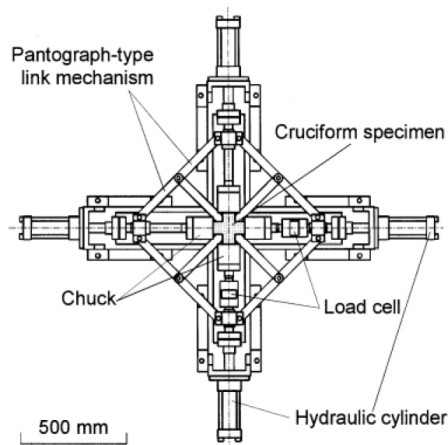


Figure 1. Servo-controlled hydraulic biaxial testing apparatus [10]

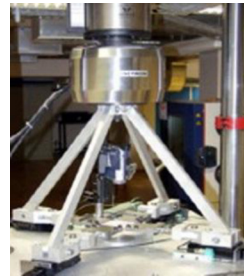


Figure 2. Biaxial linkage for compression test machine [11]

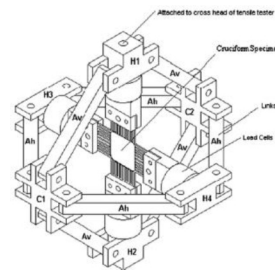


Figure 3. Pantograph mechanism for tensile test machine [12]

Testing equipment

To achieve in-plane equi-biaxial loading along each arm of cruciform specimen, a biaxial testing attachment on a universal material test machine DDL100 was designed. A coniform metal block (see Figure 4) was attached to the loading head of the test machine and served to transform vertical translation to perpendicular directions along two pairs of arm in the horizontal specimen plane. Four customized load cells [13] were mounted between the tackles and the specimen's arms. Digital image correlation (DIC) method was applied in deformation measurement. It is well known that DIC is the most promising technique because of its full-field character in the review of Ramault et al. [14]. To capture the full field deformation of gauge section in cruciform specimen, one mirror (see Figure 4) was set under the base at an angle of 45 degree to the horizontal plane. Besides, cold illuminator was introduced to eliminate the heat influence on the tested material.

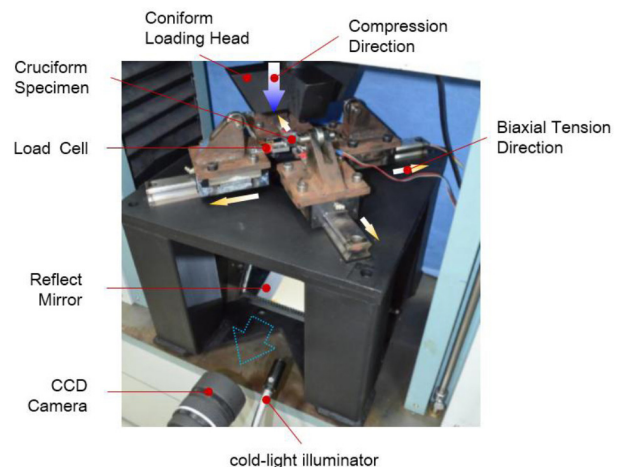


Figure 4. Set-up of biaxial testing attachment presented in this paper

One advantage of this biaxial testing attachment is that it can achieve biaxial loading at constant velocity throughout the test. Figure 5 and Figure 6 present kinematic analysis of the Fraunhofer's link mechanism attachment [11] and the biaxial testing attachment used in this study, respectively. For Fraunhofer's apparatus, biaxial loading speed changes since θ changes throughout the test. For the biaxial testing attachment used in this study, biaxial loading speed remains constant since θ is a geometric invariant. Besides, compared with those exiting link mechanism attachments, application of rail-tackle systems and pulleys can effectively reduce the friction effect.

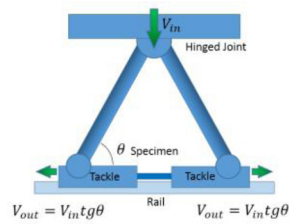


Figure 5. Speed analysis schematic of Fraunhofer's link mechanism attachment [11]

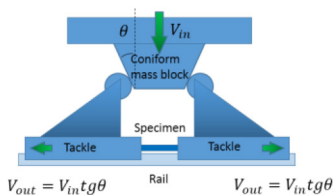


Figure 6. Speed analysis schematic of biaxial testing attachment presented in this paper

Cruciform Specimen

The design of biaxial cruciform specimen is another issue. So far there is no standard defining geometry of cruciform specimen. Currently, FE modeling is often used to optimize the geometry of cruciform specimen.

Smits et al. [15] suggested that a successful biaxial stress test with cruciform specimens require five conditions as follows:

1. Maximization of the region of uniform biaxial strain.
2. Minimization of the shear strain in the biaxial-loaded gauge section.
3. Minimization of the strain concentration outside gauge section.
4. Specimen failure in the biaxial-loaded gauge section.

According to some recommendations on the design of cruciform specimen provided by existing studies [15, 16, 17, 18, 19] and our own experience, a basic geometry of cruciform specimen was put forward on thermoplastic polymer plates with thickness of 3 mm as presented in Figure 7. Concaved corners with radius of 2.5mm and a recess in central gauge section ensure the strain concentration location. Referring to Moreno's design [20], two-stage transition of thickness is set at all the four sides when the recess is milled to impair stress concentration caused by geometrical discontinuity, as

shown in Figure 8. The thickness of each stage, t , is the only parameter to be optimized in the design of biaxial tension specimen in the present paper.

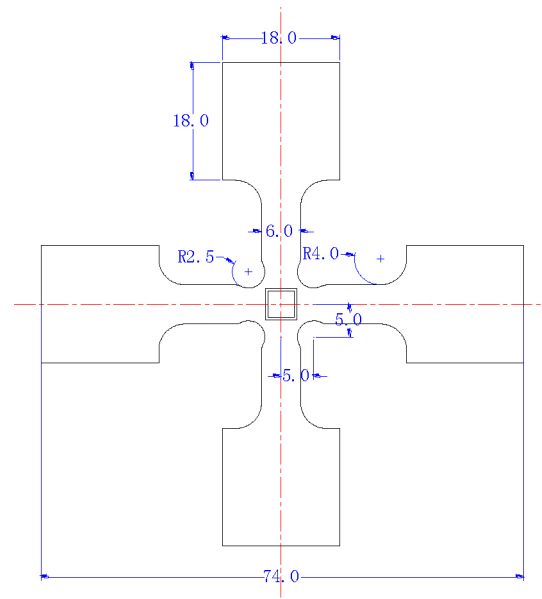


Figure 7. Basic geometry of the cruciform specimen (units: mm)

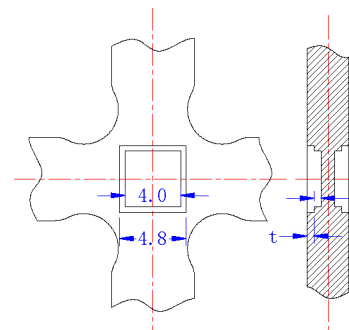


Figure 8. Geometrical parameters in gauge section of the cruciform specimen (units: mm)

Finite element model of 1/8 specimen used in the optimization is presented in Figure 9. The element formulation is fully integrated solid element. The material model SAMP-1 in LS-DYNA was used. The input material properties are given in Table 1 and Figure 10.

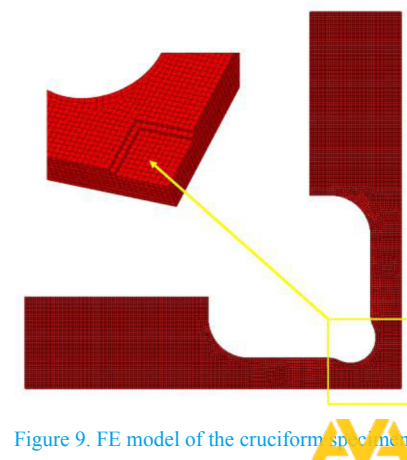


Figure 9. FE model of the cruciform specimen