Finite Element Analysis for Thermoforming Process of Starch/ Biodegradable Polyester Blend

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Abstract

The objective of this work is to study the behaviour during sheet thermoforming process of a Tapioca starch-biodegradable polyester (Enpol[TM]) blend with the mixing ratio of 50:50 by weight. The mechanical behavior of the material extruded in the form of thin sheet was studied by means of compression tests with varying strain rates at temperatures ranging from between 363 K to 393 K. The Elastic–Perfectly Plastic material model was used to capture the compressive deformation behavior of the material. It was found that the model described reasonably well the behavior of the material and the 2D Finite element simulation with Elastic–Plastic material model gave good representation of the real thermoforming process.

***Keywords**: Bioplastics, Thermoforming, Finite Element Analysis*

1 Introduction

Bioplastics is derived from renewable resources and could be degraded more easily than petroleum-based plastics. With the growing environmental concerns and the realization that petroleum resources are limited, a wide range of biodegradable plastics have been developed in the last two decades in order to reduce the amount of long-lived petroleum-based plastics wastes. Starch-based bioplastics is one class of bioplastics, which can be further divided into three categories [1]: (1) thermoplastic starch materials; modified starch with plasticizing additives; (2) blends of starch and biodegradable plastics; (3) plastics whose monomers are biochemically derived from starch. Among these materials, the blends of starch and biodegradable plastics have been developed into packaging materials and biomedical applications such as bone replacement, tissue scaffolds and drug-delivery systems [2].

Starch-based bioplastics can be processed by several techniques traditionally undertaken with petroleum-based plastics. However, processing of starch-based bioplastics could be very different from petroleum-based plastics because of the highly-branched molecular structure and the hydrophilic nature of starch. A number of computational modeling of thermoforming processes of petroleum-based plastics have been developed and proposed ([3],[4],[5],[6],[7],[8]), but only few for starch-based bioplastics. Szegda et al. [1] employed finite element techniques to model thermoforming processes of Plantic[TM], commercial starch-based thermoplastics, in order to predict its thermoformed structure. Even

though the prediction did not perfectly match the experimental data, the model could capture some features of the thickness variation. Further model modifications such as the considerations of non-uniform initial thickness and the moisture and temperature effects were necessary to improve the model predictions.

The paper is among the first attempts to develop a simple computational modeling based on finite element techniques to predict the behavior of a blend of starch/biodegradable plastic, Enpol^{TM}. The mechanical behavior of the material extruded to the form of thin sheet was studied by means of compression tests at temperatures from 363 toto 393 K and at strain rates of 0.1 and 0.5 s^{-1}. Elastic-plastic material models was used to capture the compressive behavior of the material and 2-dimensional finite element simulation of the sheet thermoforming process was presented.

2 Experimental Work

2.1 *Materials*

The polymer in this study was tapioca starch-Enpol^{TM} blend, provided by DES Co.Ltd.(Thailand). Enpol^{TM} is a fully biodegradable aliphatic polyester resin developed by IRe Chemical Ltd. (Seoul, Korea). The ratio of tapioca starch to Enpol^{TM} was 50:50 by weight.

2.2 *Samples preparation*

The tapioca starch-Enpol^{TM} blend was extruded into thin strips with cross-sectional area of 2mm x 20mm, using a twin screw extruder (HAAKE Polylab, Rheomex CTW 100P). To eliminate moisture content, the material was dried in a hopper drier at 80^{o}C for 4 hours, prior to the extrusion process. The extruded material, shown in Figure 1, was then cut in to small thin square test pieces with dimension of 12x12x2 mm for compression tests.

Figure 1: Thin strips of extruded tapioca starch-Enpol^{TM} blend.

2.3 *Differential Scanning Calorimeter test*

The thermal analysis was performed using a Mettler Toledo Differential Scanning Calorimeter (DSC) model DSC 822 at the heating rate of 20^{o}C/min. Data from DSC showed that the blend had one endothermic melting peak between 383-403 K with the highest point located at 391 K.

2.4 *Mechanical Testing*

In order to determine the mechanical deformation behaviour of the biodegradable material, the uniaxial compression tests were performed at various temperatures ranging from 363 K to 393 K with strain rates of 0.1 and 0.5 s^{-1}. The compression tests were carried out according to ASTM D695 using an universal testing machine (Instron model 5567) equipped with a temperature control chamber. Two thin square samples described earlier were stacked up on a compression platen as shown in Figure 2. The dependence on temperature and strain rate of the deformation is shown in a compressive engineering stress vs. engineering strain plot given in Figure 3. As temperature increases, the material behaves as a softer material and yield stress decreases. On the other hand, the yield strain values at different temperatures are not affected by temperature and yielding occurred at approximately the engineering strain of 0.07. As the strain rate increases the material becomes stiffer but only very slightly, thus it can be said that the deformation behaviour is almost unaffected by strain rates. When true stress are plotted against true strain at different temperatures and a strain rate of 0.5 S^{-1} in Figure 4, it can be observed that the deformation undergoes without increase in stress after yielding and that it deforms in elastic-perfectly plastic manner. From the tests conducted, the optimum processing condition was achieved at 393K with strain rate of 0.5 S^{-1}. At this condition, the compressed specimen was easily deformed and had good surface appearance. For other conditions, cracks appeared on the specimen's surface. These test results also provided material's properties used in the subsequent finite element modelling.

2.5 *Sheet thermoforming*

Sheet thermoforming was performed by a match mould compression method with die and punch configuration shown in Figure. 5. Before subjected to compression, a strip of specimen was heated at 393 K

for 20 minutes. The compression sheet thermoforming process was carried out at 393 K and the punch was set to travel 10mm in 4 seconds. An example of stamped specimen strip is shown in Figure 6.

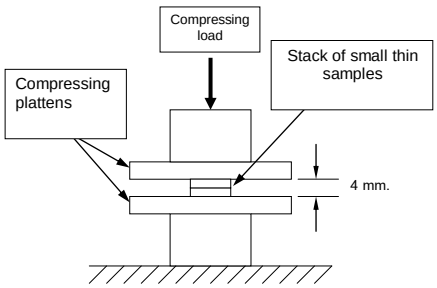

Figure 2: Compression test arrangement

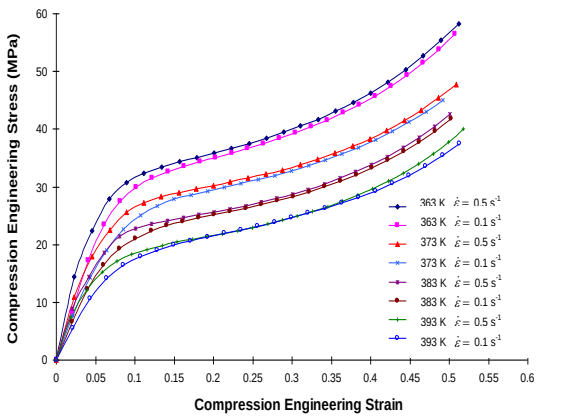

Figure 3: Plot of compressive engineering stress vs. engineering strain at different temperatures and strain rates

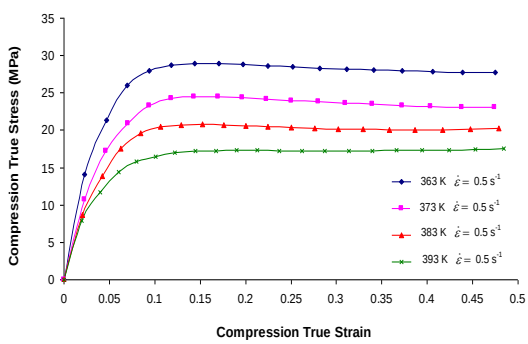

Figure 4: Plot of compressive true stress vs. true strain at different temperatures.

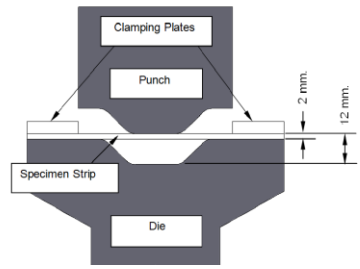

Figure 5: Sheet thermoforming test arrangement

Figure 6: Specimen after the sheet thermoforming process

3 Finite Element Simulation

3.1 *Material Model*

Since the deformation behavior was found to be temperature dependence, strain rate insensitive with no strain hardening after yield, thus it was modeled with a standard isotropic elastic-perfectly plastic material model inbuilt in a commercial finite element package ABAQUS 6.5 [9]. The input material's properties needed are Young's modulus, Poisson's Ratio and true yield stress. Young's modulus and true yield stress are temperature dependent and were determined from true stress-strain curves shown in Figure 4. These values are tabulated in Table 1. Poisson's ratio of the materials was assumed to be 0.4. A comparison between the experimental data and finite element simulation using a single 3D element (C3D8H) with elastic-perfectly plastic material model is given in Figure 7 and a very good agreement of to the data can be observed.

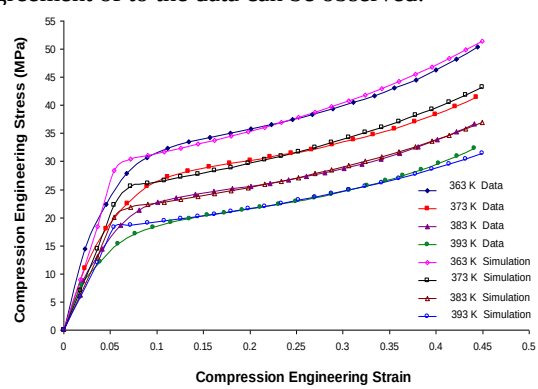

Figure 7: Comparison between experimental data and finite element simulation with elastic-perfectly plastic material model.

Table 1: Material's Properties for elastic-perfectly plastic material model.

Temperature (K)	Young's Modulus (MPa)	True Yield stress (MPa)
363	484.387	28.307
373	380.168	23.757
383	341.897	20.313
393	314.767	17.293

3.2 *Finite element simulation of thermoforming process.*

A finite element model was developed to simulate the matched mould thermoforming process at 393 K described in section 2.5 using a finite element package ABAQUS 6.5. The process was symmetrical and thus one-half of the system was modeled. 2-D shell elements (S8) were employed incorporating with the isotropic elastic-perfectly plastic material model. The die/punch was modeled as a rigid body. The die and the specimen areas contacting with specimen holders were kept stationary and modeled with fixed boundary conditions, while the punch and the other specimen areas were modelled as non-stationary with movable boundary conditions. Frictionless conditions were employed for both interfaces between specimen/die and specimen/punch. In modelling the compression process, the punch was set to travel 10mm in 4 seconds. Figure 8, presents the distribution of thickness of the specimen predicted by the finite element simulation and the Mises stress distribution is given in Figure 9. The thickness and stress distribution give us cautions to the areas that are becoming too thin and highly stressed during the forming process. A comparison between the compressing load measured during the forming process and the prediction from the simulation are given in Figure 10. A good correlation between the simulation result and experiment data can be observed. This gives us a confidence to use the described finite element analysis methodology to further simulate match mould thermoforming process of the starch/biodegradable polyester blend of other mould shapes and sizes.

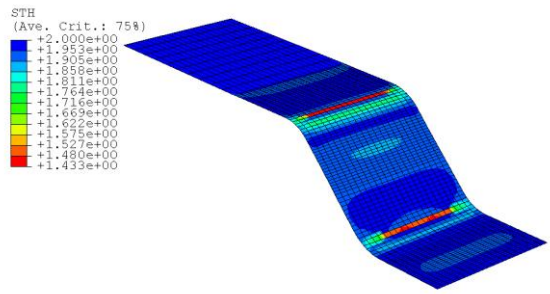

Figure 8: Distribution of the specimen's final thickness predicted by the finite element simulation.

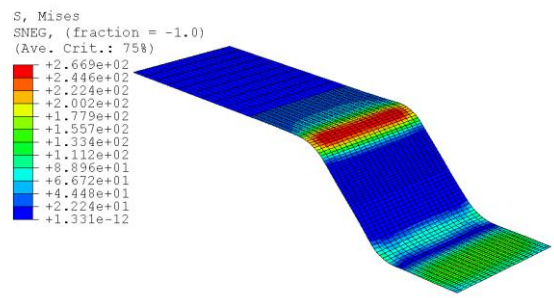

Figure 9: Distribution of Von Mises' stress in the moulded specimen predicted by the finite element simulation.

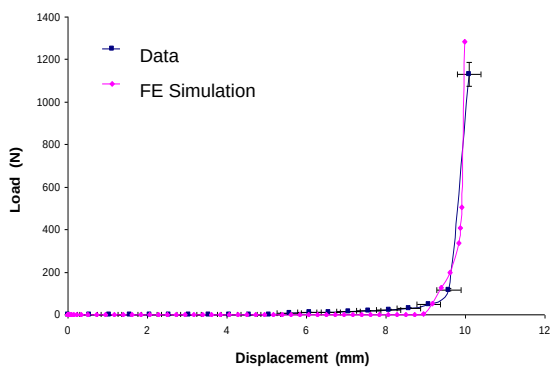

Figure 10: Comparison between the compressing load measured during the forming process and the prediction from the simulation.

4 Conclusions

In this presented work, sheet thermoforming process of Tapioca starch-biodegradable polyester (Enpol^{TM}) blend with the mixing ratio of 50:50 by weight was studied. The mechanical behavior of the material extruded in the form of thin sheet was studied by means of compression test at temperatures between 363 K to 393 K and at different strain rates. It was found that temperature of 393 K and strain rate of 0.5 s^{-1} gave the most satisfying condition for the sheet stamping process. Elastic–Plastic material models was selected for capturing the compressive deformation behavior of the material. It was found that the Elastic–Perfectly Plastic model described reasonably well the behavior of the material. The 2D Finite element simulation of a sheet stamping thermoforming process with Elastic–Plastic material model can give good representation of the real thermoforming process. This gives us a confidence to use the described finite element analysis technique to further simulate match mould thermoforming process of the starch/biodegradable polyester blend of other mould shapes and sizes.

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