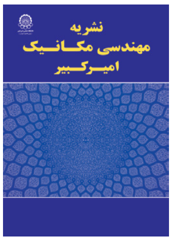

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(5) (2020) 281-284
DOI: 10.22060/mej.2019.15196.6057

Experimental and Simulation Study on the Warpage of Polyamide 6 Based on Thermo-Mechanical Behavior of Material Using Uniaxial Tensile Test

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ABSTRACT: This research focuses on investigating the time-dependent behavior of polyamide 6 and using the generalized Maxwell model for prediction of this behavior. To achieve this goal, tensile specimens are manufactured via injection molding process and then are tested based on stress relaxation trials. Moreover, two specimens manufactured with different mold temperatures are tested to investigate the effect of the mold temperature on the time-dependent behavior of this kind of polymer. Finally, to evaluate the ability of the generalized Maxwell model to predict the time-dependent behavior of polyamide 6 correctly, a finite element simulation is carried out via a link between the Moldflow and ABAQUS software. In these simulations, the amount of warpage occurring in the specimen obtained from this model is compared with experimental finding. The results show that the mold temperature has a negligible effect on the time-dependent behavior of this polymer and also, there is a good agreement between simulation and experimental results of warpage with a mean error of 13%. Therefore, the generalized Maxwell model is good enough to predict the time-dependent behavior of polyamide 6. On the other hand, this methodology can be used prior to making real parts to prevent the high cost of manufacturing.

Review History:

Received: 10/28/2018
Revised: 12/21/2018
Accepted: 2/4/2019
Available Online: 2/13/2019

Keywords:

Thermo-mechanical behavior
Viscoelastic
Warpage
Polyamide 6

1. INTRODUCTION

It is important to investigate the thermo-mechanical properties of materials for designing new products. One of these materials is a thermoplastic polymer which exhibits viscoelastic behavior at temperatures above its glass transition temperature (*Tg*), making it time-dependent material. It means that the stress depends on the time and strain rate [1]. A lot of different models have been developed to describe the viscoelastic behavior of polymers [2]. These models are based on different combinations of either linear spring and dashpot or nonlinear spring and dashpot [3, 4]. Gudimetla and Doghri [5] developed a viscoelastic-viscoplastic model for polymers and Spathis and Kontou [6] presented a viscoelastic model for polymer-based composites. Moreover, some other research focused on the effect of different parameters on the viscoelastic behavior of polymers. Starkova et al. [7] investigated the effect of temperature, strain rate and moisture on the linear viscoelastic behavior of polyamide 66. As can be seen, there are a few research focusing on the Polyamide 6 (PA 6) and most of them are experimental works which are costly. Therefore, it is crucial to conduct a simulation prior to producing a specimen for investigating the effect of different parameters on the polymer behavior to save time and decrease costs.

In this work, the time-dependent behavior of polyamide 6 by using the generalized Maxwell model for prediction of this behavior was investigated. To achieve this goal, tensile specimens were manufactured via injection molding process and then were tested based on stress relaxation trials. Moreover, two specimens manufactured with different mold temperatures were tested to investigate the effect of the mold temperature on the time-dependent behavior of this kind of polymer. Finally, to evaluate the ability of the generalized Maxwell model to predict the time-dependent behavior of polyamide 6 correctly, a finite element simulation was carried out via a link between Moldflow and ABAQUS software. In these simulations, the amount of warpage occurring in the specimen obtained from this model was compared with experimental finding.

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2. LINEAR VISCOELASTIC

Different models have been developed to predict linear viscoelastic behavior of polymers. In these models, a linear spring is used to represent elastic behavior and a linear dashpot is employed to represent viscous behavior of the polymer. One of the most comprehensive models is the generalized Maxwell model. Linear viscoelastic behavior can be defined using the Prony series, which is an expansion of the dimensionless relaxation modulus. It is expressed by the following equations:

$$g_R(t) = 1 - \sum_{i=1}^{n} g_i (1 - e^{-\frac{t}{\tau_i}}) \tag{1}$$

$$K_R(t) = 1 - \sum_{i=1}^{n} K_i (1 - e^{-\frac{t}{\tau_i}}) \tag{2}$$

where g_i, k_i,, and τ_i are the material constants.

3. EXPERIMENTAL PROCEDURE

Polyamide 6 used in this work was from DSM Co. with a grade of Akulon F223-D (the Netherlands). Specimens

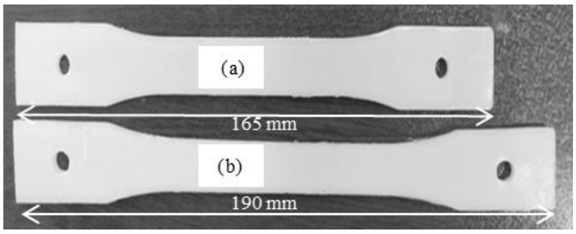

Fig. 1. Stress relaxation test specimen (a) before the test (b) after the test

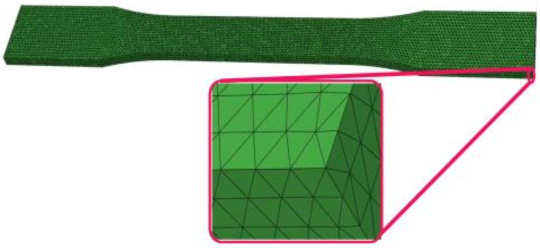

Fig. 2. Tetrahedral mesh used to discretize the model

were produced in line with type 1 from ASTM-D638 [8] standard using injection mold. The thickness of the produced specimens was 4 mm. Stress relaxation test was employed in this work to investigate the viscoelastic behavior of the polymer. The specimen was tested using a calibrated tensile test machine (STM-50, SANTAM). The tests were conducted at a temperature of 100±3 °C. At first, an initial tensile of 25 mm was applied to the specimen and then they were kept in these conditions for 50 minutes. The load and time were continuously recorded. Fig. 1 shows the specimen (a) before and (b) after the test.

4. SIMULATION

In this study, the Moldflow 2012 and ABAQUS 6.14 finite element software were used to simulate the warpage amount of specimen. The 50,426 tetrahedral elements were used to discretize the specimen. Fig. 2 depicts tetrahedral mesh used to discretize the model. It is to be mentioned that the tetrahedral edge length was also kept around 1 mm.

5. RESULT AND DISCUSSION

Fig. 3 shows the results obtained from the stress relaxation test. At first, this plot was converted to a dimensionless plot and then the Prony series were fitted to this plot to acquire coefficients of this series mentioned in Eqs. (1) and (2). Experimental dimensionless plot and fitted curve are shown in Fig. 4. It is to be mentioned that the R-square value is equal to 0.9999. Finally, the coefficients for the first three terms of this series extracted from Fig. 4 are presented in Table 1.

As mentioned earlier, two specimens were produced with different mold temperatures to investigate the effect of mold temperature on the viscoelastic behavior of PA6. Fig. 5 shows the stress relaxation plot of two specimens with a mold temperature of 25°C and 100°C, other factors being the same. As can be seen in this Figure, increasing mold temperature has a negligible effect on the viscoelastic behavior. PA6 is a semi-crystalline polymer which has both crystalline and amorphous regions. In fact, the amorphous region has a significant effect on the viscoelastic behavior of polymer and crystalline region only has an impact on the mobility of the chains in the amorphous region. According to this fact that increasing mold temperature has a minimal effect on the degree of crystallinity of polymer affecting the mobility of amorphous chains, therefore, increasing mold temperature has a negligible impact

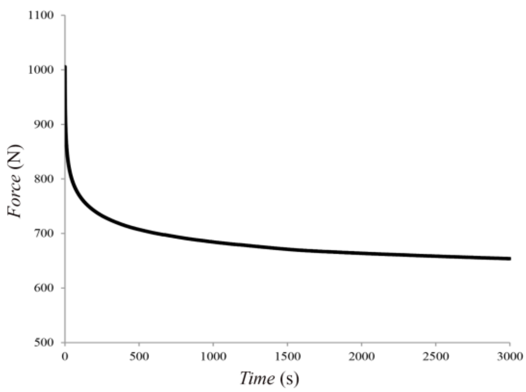

Fig. 3. The mean plot obtained from the stress relaxation test

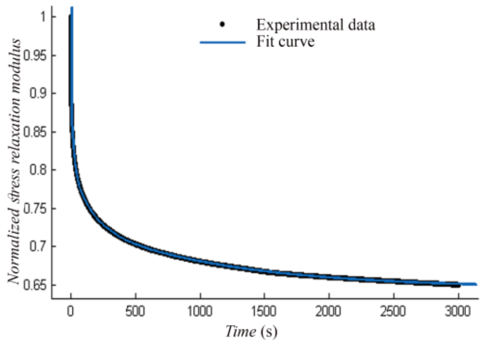

Fig. 4. Experimental results and fitted curve

Table 1. Prony series coefficients extracted from stress relaxation test

i	g_i	k_i	τ_i (s)
1	0.1	0.1	1.847
2	0.08806	0.08806	19.37
3	0.07907	0.07907	139.9

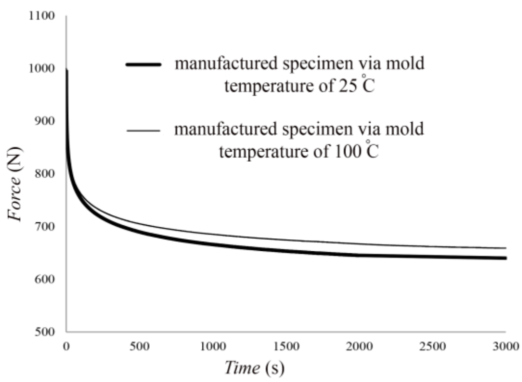

Fig. 5. The effect of the mold temperature on the stress relaxation behavior of PA 6

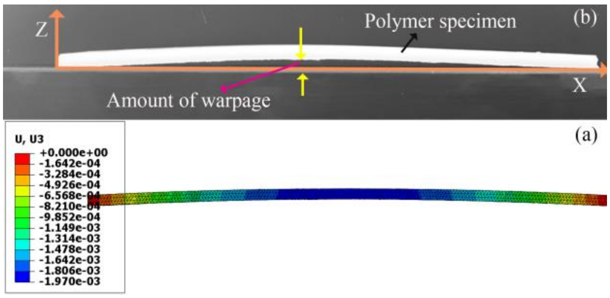

Fig. 6. The amount of warpage obtained from (a) simulation, (b) experiment

on the viscoelastic behavior of polymer [9].

Fig. 6 shows the amount of warpage occurring in the specimen both numerically and experimentally. Measured warpages obtained from experiment and simulation were equal to 2.23 mm and 1.97 mm, respectively. As can be seen, there is a good agreement between simulation and experimental results of warpage with a mean error of 13%. Therefore, the generalized Maxwell model is good enough to predict the time-dependent behavior of polyamide 6. On the other hand, this methodology can be used prior to making real parts to prevent the high cost of manufacturing.

6. CONCLUSION

The results of this work showed that mold temperature has minimal impact on the time-dependent behavior of this polymer. Moreover, there is a good agreement between simulation and experimental results of the warpage with a mean error of 13%. Therefore, the generalized Maxwell model is good enough to predict the time-dependent behavior of polyamide 6. On the other hand, this methodology can be employed prior to making real parts to prevent the high cost of manufacturing.

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