Key Engineering Materials Vols. 488-489 (2012) pp 286-289
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doi: 10.4028/www.scientific.net/KEM.488-489.386

Performance of Nylon Based Polymer Foams at Elevated Temperature under Tensile Loading

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Keywords: Cellular Solid, Polyamide Foam, Nylon, Elastic Modulus, Glass Transition Temperature

Abstract: One of the primary applications of polymer based cellular solids is to act as an energy absorbing material during impact where compressive strain rates may reach 500-800/s. In reality, impacts occur over a wide range of temperatures and velocities at different angles of incidence. Understanding and modelling the behaviour of the polymer foams requires characterisation of the material response in detail. The stress-strain response that covers both compressive and tensile behaviour for a wide range of strain rates and temperatures are needed to characterize the mechanical performance of polymer foams as polymeric foams are highly nonlinear materials that undergo large deformation in crashworthiness related cases. It is reported in literature that any increase or decrease in temperature over the glass transition region can cause changes by order of magnitude in elastic modulus of polymeric foams. However, creation of cross linking at high temperature can affect the elastic modulus.

In this work, the behaviour of two, polyamide-6 (PA-6) based closed cell foams at elevated temperatures were investigated covering the glass transition temperature. This work presents the variation of elastic and tangent modulus of two low densities PA-6 and PA-6/polyolefin (Nylon alloy) based foams. Empirical equations have been proposed to allow the prediction of modulus over a temperature range of 23°C to 120°C for these materials.

Introduction

Zotefoams plc is a world leader in the manufacture and distribution of speciality foam materials, manufactured using a unique, proprietary technology [1]. An advantage of this technology is the wide range of materials to which it can be applied. For PA-6 based materials the foaming process has traditionally been an insurmountable technical challenge or otherwise limitations have existed to the reduction in density possible.

The ZOTEK N B50 and N A30 grade foams have nominal densities of 50kg/m^3 and 30kg/m^3, respectively. N B50 is produced from a PA-6 base material and N A30 is produced from a PA-6 and Polyolefin alloy base material. Generally, the properties of both foam materials reflect those of this class of polymer, with high temperature performance, resistance to hydrocarbon fuels and oils combined with impact performance, buoyancy and low thermal conductivity from the cellular structure. It is these characteristics which make the ZOTEK N B50 and N A30 grade foams ideal for energy absorption and cushioning applications in extreme environmental conditions.

In isotropic polymer foams Young's modulus, shear modulus and Yield stress are important to be characterised [2]. Any temperature dependency of these properties must also be understood. It is reported that over the glass transition region, the elastic modulus of a polymer can fluctuate by orders of magnitude [2], however, it is also reported that this large change can be harnessed by the presence of cross linking within the base polymer of the foam [3]. As a result, characterising the variation of the elastic and tangent modulus of our foams and establishment of any linear stabilisation in behaviour as temperature increases is the goal of this research.

Method

All samples were taken from a single foam sheet to minimise the effects of density variation on results. Cylindrical, 50mm dia × 25mm thick, samples were conditioned for a minimum of 6 days at 23°C, 50% RH [4]. All dimensions were carried out in accordance with ISO 1923 [5]. Tensile tests were carried out in accordance with methods outlined as per type B specimen given in ASTM D1623-03[6] where Scotch-Weld Acrylic Structural Adhesive DP810 is used as a sample gripping method. This is supported by those investigating fatigue properties of similar materials [7]. One sample is glued between two 52 mm dia × 25 mm thick Aluminium discs and cured at room temperature and conditioned for a further 48 hrs.

The sample is encased in a thick walled brass tube and installed in to a Mayes Universal Tensile Tester with, rotating self centring hydraulic grips. The assembly is wrapped in a heating jacket whose temperature is monitored using thermocouples used to control the temperature of the sample. The sample is then conditioned for a minimum of 2 hrs after the experiment temperature is achieved.

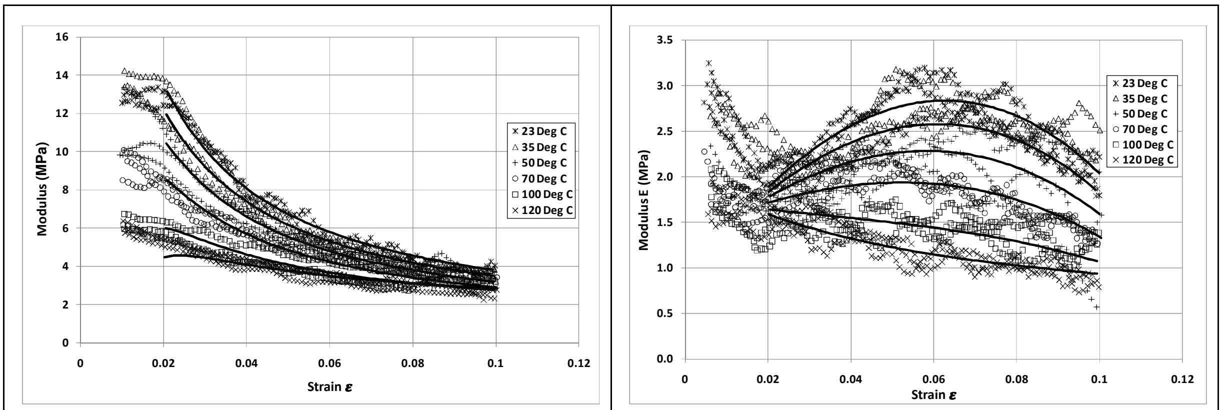
The tensile test was conducted at a strain rate of $0.01s^{-1}$ where displacement is data logged via an externally installed LDVT, connected directly to the sample holder. Expansion of metallic components due to the loading is accounted for in the data analysis. Further works are underway at higher strain rates.

Results and Discussions

All data has been analysed based on a moving point average, covering a range of approximately 20 data points over 0.01 stain range from 0.01 to 0.10 strain.

As shown in Fig.1a, the variation of tangent modulus of N B50, show a general decrease in value, with the steepest decline shown at the lower end of the temperature scale. As the temperature increases, the severity of the drop becomes less marked until the highest temperature shows a near linear relationship between tangent modulus and strain. This is a characteristic behaviour of polymer based materials. When considering the behaviour of N A30 Fig.1b, the tangent modulus increases until a peak at approximately 0.06 strain. The value then decreases, giving a non linear relationship. However, this is only evident at the lower temperatures. As the temperature increases, the fluctuation in modulus decreases until a near linear relationship is achieved at 100°C.

It is also interesting to note that at the lower end of the temperature scale, N B50 shows an approximate drop of two thirds in modulus. This is only applicable until the glass transition temperature of 50°C is reached. Once this temperature is crossed, the variation is approximately halved over a range of 0.02-0.10 strain.



a. N B50 at Strain Rate of $0.01s^{-1}$	b. N A30 at Strain Rate of $0.01s^{-1}$

Fig.1: Variation of tangent modulus vs strain at various temperature from tensile tests-Experiments and empirical curve fitting

N A30 shows that over the same range, although there is significant deviation of the modulus between 0.02 and 0.10 strain, the modulus returns to the same value. This is the case until 50-70°C (Tg) is achieved, after this the start and end value appears to differ, which becomes greater with temperature but the fluctuation is virtually eliminated. When investigating further, this behaviour is not a result of glue, machine or rate dependency.

It is reported that the elastic modulus changes by orders of magnitude over the glass transition temperature (Tg). This is not evident in this investigation. It is also reported that cross linking can and does harness this effect [3]. In order to produce this foam, cross linking is occurring, and therefore, there are not large differences in modulus. It is over the glass transition range (50-70°C) that the fluctuation in elastic modulus begins to be harnessed. For both materials, conducting tests at higher temperatures, lowers and stabilises the fluctuation in elastic modulus.

As described, the two materials show different behaviours. N A30, is manufactured from a PA-6 polyolefin alloy. By definition, this base material is a mix of two polymers and since such fluctuations are not seen in N B50, this may also contribute to the initial variation of modulus described in this paper. For N B50 and N A30, polynomials equations 1 and 2, respectively, can be used to predict the tangent modulus at a given temperature and strain. Table 1 gives the required coefficients and the accuracy of the fit. However, these functions are only valid within the limits of this paper.

$$E = a + bT + \frac{c}{\varepsilon} + dT^2 + \frac{e}{\varepsilon^2} + f\frac{T}{\varepsilon} \quad (1)$$

$$E = a + bT + c\varepsilon + dT^2 + e\varepsilon^2 + fT\varepsilon + gT^3 + h\varepsilon^3 + iT\varepsilon^2 + jT^2\varepsilon \quad (2)$$

Where:
E = Modulus in MPa
T = Temperature in °C
ε = Strain
a-j = Material dependent coefficients

Table 1: Coefficients of empirical curve fitting function

N B50 (R^2 = 0.958)									
a (10^{-1})	*b* (10^{-2})	*c* (10^{-1})	*d* (10^{-4})	*e* (10^{-3})	*f* (10^{-3})	*g*	*h*	*i*	*j*
7.86236	-1.58849	3.92949	1.89810	-1.69475	-2.09482	N/A	N/A	N/A	N/A
N A30 (R^2 = 0.843)									
a (10^{-1})	*b* (10^{-2})	*c* (10^{1})	*d* (10^{-5})	*e* (10^{2})	*f* (10^{-1})	*g* (10^{-7})	*h* (10^{2})	*i* (10^{0})	*j* (10^{-4})
5.80049	1.01808	8.32384	3.24620	-5.7209	-9.71344	-1.70370	-6.69754	6.37092	7.18107

Conclusions

The elastic and tangent modulus of both foam materials is affected by temperature. The nature of the effect can be described relative to the glass transition region of the material.

1. Below the glass transition, the elastic modulus is higher, however large fluctuations are observed in tangent modulus as strain is increased
2. Above the glass transition, the elastic modulus is lower, however there is little fluctuation as strain is increased, therefore a more constant behaviour can be assumed

The tangent modulus of both above and below the glass transition region for both foam materials can be predicted using Eqs. (1) and (2).

Acknowledgements

The authors would like to acknowledge the financial support from EPSRC Award CASE/CNA/06/29. Many thanks go to the technical staff at Zotefoams plc for the supply of the samples. In addition our thanks also go to Bryan Ruby and Chris Pickles for the manufacture of the test fixtures.

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