Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 4, Issue 2 / 2019, pp. 131 - 144
http://doi.org/10.56958/jesi.2019.4.2.131

A. Mechanical Engineering

Received 4 March 2019 Accepted 30 May 2019
Received in revised form 7 May 2019

Onset of densification and energy absorption efficiency of polyurethane foams

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Abstract. Polyurethane foams with densities of 35, 93 and 200 kg/m^3 were tested in compression at three levels of temperatures as: -60°C, 23°C, and 80°C. The influence of speed of testing from 2 mm/min up to 6 m/s (0.0014 to 545 s^{-1}) on the response of the foams is analyzed. Testing is done separately on the rise direction and on the in-plane direction of the foams and differences in their behavior are commented. With interpolation functions which approximate the plateau and densification region the specific strain energy is calculated together with the energy efficiency and onset strain of densification. A Nagy type phenomenological strain rate dependent model is proposed to generate engineering stress-strain curves and is validated through comparison with experimental stress-strain curves obtained at different speeds of testing. Starting from a reference experimental curve, two material parameters which are density and temperature dependent are established. Comments on the onset of densification and energy efficiency as function of the varying parameters are done.

Keywords: speed of testing, temperature, strain energy, onset of densification, energy efficiency.

1. Introduction

Foams are characterized by energy absorbing capabilities combined with a low weight and are used as core materials in structural sandwiches and as absorbers of impact energy in typical applications. Foam materials have a cellular structure and hence behave in a complex manner, especially under conditions of progressive crush. Besides their excellent ability for energy adsorption, good damping behavior, sound absorption and excellent heat insulation, they have a high specific stiffness combined with a low weight. A good knowledge of the behavior of

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different grades of foams is important for being able to design high performance sandwich composites adapted to the special needs of a particular application (Gibson and Ashby, [1]; Mills, [2]).

Strain rate and density effects on the crush behavior of foams were studied, among others, by Li et al. [3], Li et al. [4], Li and Mines [5]. Following, Mines [6] studied strain rate effects on Divinycell PVC foam, Rohacell PMI foam and Alporas aluminum foam. His impact tests used standard static test rigs, with the higher rate of loading being achieved using a high rate servo hydraulic machine which can achieve crosshead speeds of up to 10 m/s. For this speed of testing and a specimen height of 50 mm the initial strain rate is 200 s^{-1}. Shen et al. [7] did similarly high rate compressive tests reaching 220 s^{-1} on the Alporas aluminum foam and studied the strain rate effect on the densification strain; this issue will be extensively discussed later. Viot et al. [8] carried out tests on polypropylene foams under high strain rate compression tests on a flywheel for higher strain rates and the material behavior has been determined as functions of two parameters, density and strain rate. The sample compression was filmed with a high-speed camera monitored by the flywheel software as to obtain displacement and strain fields during tests. A modified split Hopkinson pressure bar procedure was used by Chen et al. [9] to conduct dynamic compressive experiments for polyurethane (PUR) foams with four densities in the high strain rate from 1000 to 5000 s^{-1} and they showed that the dynamic stress-strain curves are of very similar shapes, being insensitive to the strain rate before densification, but for each density the onset of densification occurs at higher strains as strain rate increases. For a low-density polymeric foam and intermediate strain rates from 0.05 to 2700 s^{-1}, compressive tests done by Song et al. [10] leaded to the conclusion that the modulus of elasticity, cell-collapse strength, and plateau stress increase with increasing strain rate. Saint-Michel et al. [11] tested rigid polyurethane foams with relative density between 0.3 and 0.85 by proposing a phenomenological approach to be used for a non-linear behavior which also enables a correct simulation of the ageing effect. Avalle et al. [12] proposed a phenomenological model being able to describe the dependency on the density value by a reduced number of experimental tests needed for the model parameter identification, thus establishing the foam optimal parameters, and in the final design stage the optimal density of the foam for a specific structural component. Other studies, as those done by Ouellet et al. [13], Gong et al. [14], and Gong and Kyriakides [15] must be mentioned.

When the temperature effect is added to strain rate and density influences on foams behavior, phenomena become more complicated as the interdependency between these parameters is difficult to be quantified. Cady et al. [16] did high strain rates tests on closed-cell aluminum foam using a split-Hopkinson pressure bar and quasi-static and intermediate strain rate tests on a hydraulic load frame. They observed a small change in the flow stress as a function of strain rate, but a strong temperature dependency under both quasi-static and dynamic loading. The mechanical response over the entire range of strain rates indicated a non-uniform deformation. Behavior of three rigid PUR foams was studied by Song et al. [17] by employing a modified split Hopkinson pressure bar at temperatures from -54 °C to 74 °C, and a strain rate of 3000 s^{-1}. Arezoo et al. [18] tested four different densities of Rohacell foam at strain rates from 1000 to 5000 s^{-1} and temperatures between -70°C and 200°C. They found that compressive collapse stress is increasing with increasing strain rate and decreasing temperature, but this tendency is inverted at very low temperatures or very high strain rates. A time-temperature superposition was employed to map the temperature sensitivity of the foams to strain rate influence. The applicability of such a time-temperature superposition principle was detailed before by Zhao et al. [19].

Present paper is dedicated to the study of the influence of foam density, speed of testing and temperature and on the onset of densification and efficiency of PUR foams. Comments on the influence of these parameters are done and conclusions regarding the PUR foams behavior are drawn.

2. Mechanical testing in compression of the PUR foams

Compressions tests were done on a hydraulic MTS testing machine specially conceived for testing polymers, [20]. Testing speeds started from 2 mm/min going up to 40000 mm/min (2, 6, 18, 54, 125, 200, 350, 500, 1000, 2000, 3500, 6000, 10000, 20000, 30000, 40000 mm/min) and then 1, 3, and 6 m/s (360000 mm/min). Foams of densities 35 and 93 kg/m^3 foams were produced by a Romanian company and the 200 kg/m^3 foam is Divinycell H 200, produced by DIAB. As the specimens were cut from PUR plates of given thickness the approximate specimen dimensions, with the height being the last of the three dimensions, were: 25×25×24 mm for 35 kg/m^3, 15×15×11 mm for 93 kg/m^3, 12×12×11.9 mm for 200 kg/m^3. Therefore, the initial strain rate started from a value as low as 0.0014 s^{-1} to a maximum value of 545 s^{-1}. For the tested compression specimen, the *rise direction* of the foam was notated as *direction 3* and *one of the in-plane directions* as *direction 1*; some preliminary tests showed that on both the in-plane directions practically the same values of the mechanical properties were obtained. The solid density (both for rigid and flexible PUR foams) is reported by Gibson and Ashby as being 1200 kg/m^3. Therefore, for the three foams the relative density is approximately: 0.03, 0.08, and 0.17.

For the compression testing a specially designed MTS Composite testing machine, capable of reaching 8 m/s with the help of a three stages valve (valve needed for speeds higher than 0.7 m/s) was used. This machine is also equipped with a piezoelectric quartz-crystal load cell washer. In our tests we haven't exceeded 6 m/s for safety reasons, due to the small height of our specimens. The machine is controlled by creating a command line program that carries on the task required for testing. The acquisition has been done by using a fast measurement buffer of 1024 values at a rate of 35 kHz for the beginning of the test and by using the highest possible acquisition rate provided by the machine in a normal manner at 5 kHz till the end of the test. In order to be sure of the generated results, a comparison has been done by using a SIGMA oscilloscope manufactured by Nicolet Technologies capable of measurements up to 500 kHz. By using the piezoelectric load cell washer together with the oscilloscope, the data have been compared to the data obtained by using only the machine, and later we took the decision to use only the results provided by the testing machine as they proved to be correct. On the other hand, this method is simpler, and by using the crosshead movement to measure displacement and calculate strain, the conventional characteristic curve is generated.

All tests were done at three levels of temperatures as: -60°C, 23°C, and 80 °C. For each testing case (density, temperature, speed) five specimens were tested and the representative one was selected; if a test gave suspicious results it was disregarded. The obtained stress-strain curves were presented previously, and more comments were done elsewhere, [21].

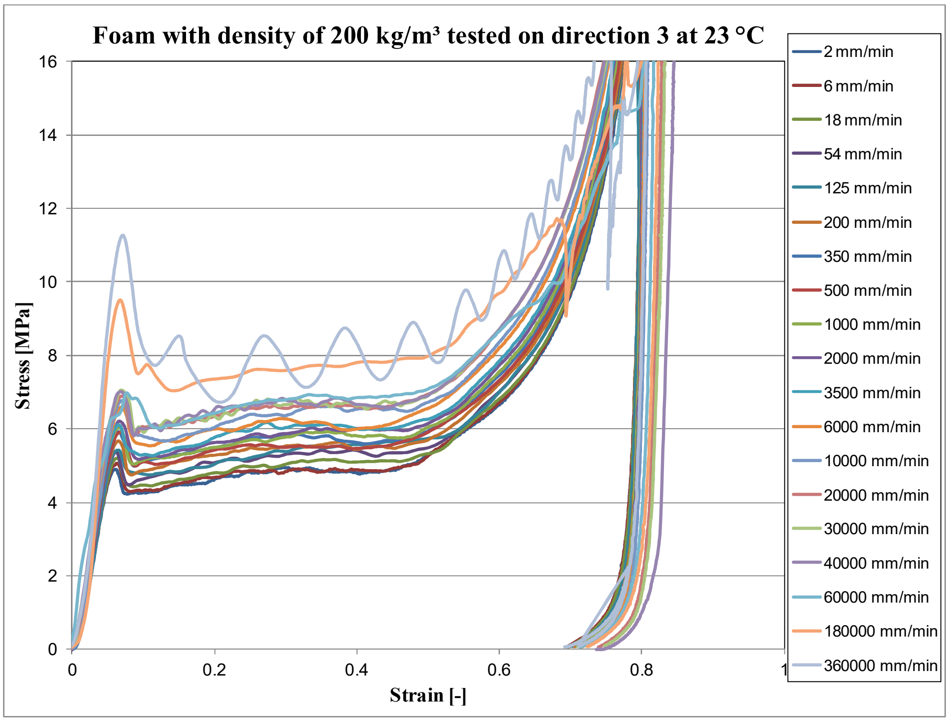


Fig. 1. Compression engineering stress-strain curves obtained experimentally at 23 °C (200 kg/m^3).

Only as an example, in Fig. 1 are shown the experimentally obtained engineering stress-strain curves obtained on *direction 3* for all the 19 speeds of testing for the 200 kg/m^3 density foam, at 23 °C. As initial strain rate is increased the curves are shifting upwards having a bigger difference between the upper and lower yielding (crush) stress. The *plateau stress* is defined hereby the stress where the plateau region starts; this stress corresponds to a strain of about 10%; in some cases, for higher speeds of loading – due to inertial oscillations, a difference of ±2% was observed. A slight hardening is noticed till the onset of densification. At higher testing speeds the measurement of foam deformation during dynamic crush is not a simple task as inertial effects are present. Care must be exercised in filtering out unwanted oscillations. Even so, for higher testing speeds, especially at 3 and 6 m/s foam deformations are showing important variations, becoming greater for the lower temperature.

3. Reconstruction of stress-strain curves

Several factors such as the mechanical properties of the constitutive material, foaming process, porosity (directly affecting apparent density) and microstructure can lead to the design of a foam material in order to get the mechanical characteristics needed for a particular application. Consequently, the proper mechanical characterization of such a material and the identification of the mathematical model parameters have at its bases a high number of experimental tests. As so, a suitable approximation of the engineering stress–strain curve has been proposed by several authors. To perform a finite element calculation for a structural analysis a micro-mechanical model is not strictly needed, but it is enough to provide a reliable representation of the engineering stress-strain curve. One can rely on a phenomenological model, as the well-known Rusch model, [22-24], which does not consider the density effect, or consider the Gibson and Ashby density dependency (of micro-mechanical type) or other laws, but with limited applicability. While several phenomenological models are intended to fit the experimental results but do not account for the density dependency of the foam mechanical characteristics, Avalle et al. [25] have proposed a model as to improve the fitting capabilities of previous models. Clearly, the type and quality of the mathematical model can reduce significantly the number of tests needed to have a complete understanding of the particular design relying on the strain rate, interval of temperature variation, and last but not least the apparent density of the foam as to consider an optimal density to improve foam efficiency.

The numerical interpolation of our experimental data uses a fifth degree polynomial function in the elastic region and at the beginning of the plateau region where appears sometimes a significant difference between the upper and the lower yield limit as follows

$$\sigma(\varepsilon) = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5\,, \tag{1}$$

where $C_0\,, C_1\,, C_2\,, C_3\,, C_4$ and C_5 are constants to be established for each particular test.

In the plateau and densification regions the function which approximates the characteristic curve is of the form:

$$\sigma(\varepsilon) = \sigma_p + A_1 e^{-\frac{\varepsilon}{t_1}} + A_2 e^{-\frac{\varepsilon}{t_2}}\,, \tag{2}$$

where σ_p is the stress at the beginning of the plateau region, and $A_1,\ A_2, t_1$ and t_2 are parameters to be established for each test. These ones include the effects of density and strain rate.

Li et al. [26] have shown that the method based on the energy absorption efficiency curve gives unique and consistent results and makes possible the establishing of a representative strain at the onset of densification. The specific strain energy can be calculated by using relation (3) as

$$W = \int_{\varepsilon_p}^{\varepsilon} \left(\sigma_p + A_1 e^{-\frac{\varepsilon}{t_1}} + A_2 e^{-\frac{\varepsilon}{t_2}} \right) d\varepsilon. \tag{3}$$

The energy absorption efficiency for a specific strain is defined by

$$E(\varepsilon) = \frac{1}{\sigma(\varepsilon)} \cdot W\,. \tag{4}$$

For an anisotropic cellular specimen, the value of the energy absorption efficiency depends on the direction in which the compressive stress-strain curve is obtained. The energy absorption efficiency is used to determine the onset strain of densification from relation

$$\left.\frac{dE(\varepsilon)}{d\varepsilon}\right]_{\varepsilon=\varepsilon_D} = 0, \tag{5}$$

at which it is obtained a maximum in the energy efficiency - strain curve.

Just to suggest the calculus which has been done for all three densities of foams at the three testing temperatures over the domain of crosshead speeds, in Tables 1 and 2 are given the constants and parameters established from the experimental data and by using relations (1) and (2) for the foam of density 200 kg/m^3 on *direction 1*, at the temperature of 23°C. At the same 23°C temperature, as seen in Table 3, the average energy efficiency is about the same on both directions of testing regardless the speed of testing, but the specific strain energy increases with the speed of testing, and is greater on the rise direction of the foam (*direction 3*) than on the in plane direction (*direction 1*).

Table 1. Coefficients of the polynomial function for the foam of density 200 kg/m^3 tested on *direction 1* (23 °C).

Speed [mm/min]	2	54	500	6000	20000	40000	60000	180000	360000
C_0	-0,014	-0,0399	0,0473	0,04699	0,0886	0,09886	0,17747	-0,847	-0,035
C_1	5,0933	6,11452	43,548	43,7971	33,1756	34,1228	87,2520	211,64	159,17
C_2	3459,4	5131,50	2315,4	3449,8	4452,2	4212,1	551,7	-2457	-678
C_3	-51206	-110677	-41693	-78054	-108541	-91383	-19870	13258	-8819
C_4	-3072	736407	103463	537455	925355	624527	145246	-32394	77879
$C_5\times E$+05	21,2	-9,78	7,58	-10,5	-27,7	-12,2	-3,49	0,261	-1,65

Table 2. Parameters of the exponential function for the foam of density 200 kg/m^3 tested on *direction 1* (23 °C).

Speed [mm/ min]	2	54	500	6000	20000	40000	60000	180000	360000
σ_p	3,113	3,536	3,59948	4,0231	4,31821	4,4744	5,67512	5,10927	5,5807
A_1	1,24E-02	1,40E-03	1,26E-02	1,32E-04	0,00397	0,0022	0,00759	6,52E-16	0,0307
t_1	-0,12	-0,093	-0,1162	-0,0721	-0,1038	-0,0956	-0,1203	-0,0233	-0,1536
A_2	3,27E-10	1,40E-03	6,66E-10	2,28E-02	3,97E-03	2,20E-03	7,59E-03	1,34E-01	3,07E-02
t_2	-0,03	-0,093	-0,0355	-0,1322	-0,1038	-0,0956	-0,1203	-0,1806	-0,1536

Table 3. Values of average energy efficiency and specific strain energy for the foam of density 200 kg/m^3 (23 °C).

Speed [mm/min]	Energy efficiency [-]		Specific strain energy [J/cm^3]	
	direction 1	*direction 3*	*direction 1*	*direction 3*
2	0.40	0.43	1.76	2.72
54	0.43	0.47	1.93	2.89
500	0.41	0.45	2.05	3.15
6000	0.41	0.45	2.30	3.38
20000	0.41	0.45	2.37	3.64
40000	0.43	0.46	2.46	3.72
60000	0.44	0.48	3.36	4.10
180000	0.42	0.50	3.69	4.62
360000	0.43	0.44	3.79	4.80

The variation of the specific strain energy with speed of testing is shown in Fig. 2 for the three temperatures and the three densities on the rise direction (*direction 3*), and in-plane direction (*direction 1*).

From the presented results it is evident that for the lower density of 35 kg/m^3 the speed of testing and temperature do not influence significantly the absorbed specific strain energy which is low and mostly constant. For 93 kg/m^3 the specific strain energy starts to increase slightly with the speed of testing at 80 ºC on *direction 1* and more on *direction 3*. As temperature decreases to 23 ºC and -60 ºC the increase of speed of testing increases somehow the strain energy, but it remains around 1.5 J/cm^3 even for the rise direction at -60 ºC. Only for the highest density of 200 kg/m^3, the speed of testing, direction of testing, and temperature, influence significantly the absorbed specific strain energy. As an example, for -60 ºC the increase is from 5.6 J/cm^3 at 2mm/min to 7.8 J/cm^3 at 6 m/s (360000 mm/min), that is with almost 40%.

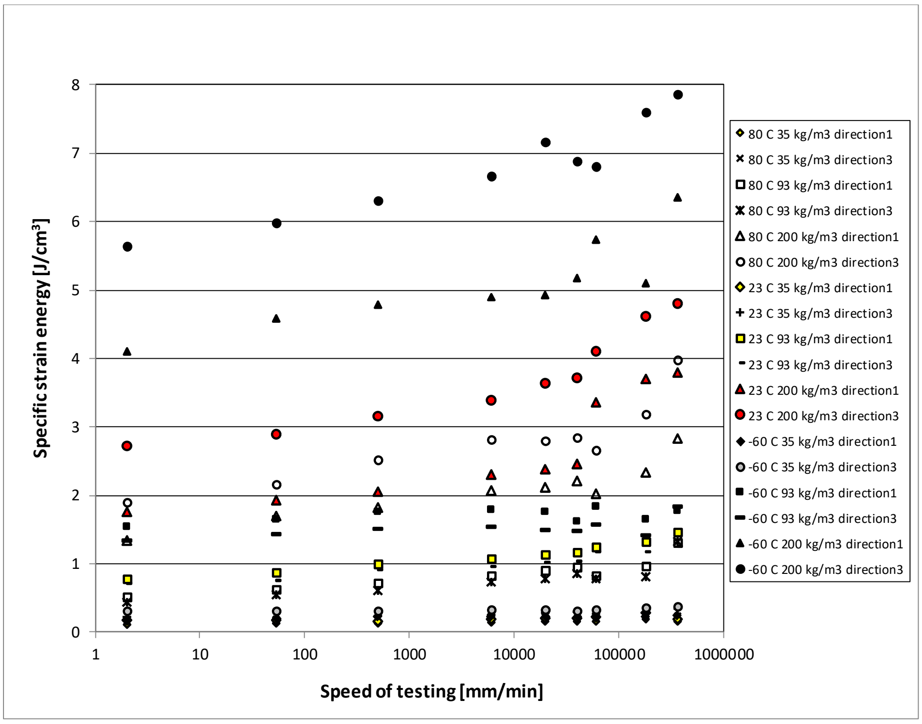


Fig. 2. Variation of absorbed specific strain energy with speed of testing as a function of foam density and temperature of testing.

So, essentially, low temperatures and high speeds of testing lead to the increase of absorbed specific strain energy.

4. Model for generating stress-strain curves

A modified Nagy model is proposed with the relation

$$\sigma = \sigma_0(\varepsilon_0)\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{a+b\varepsilon_0}, \tag{6}$$

where $\sigma_0(\varepsilon_0)$ and $\dot{\varepsilon}_0$ are established experimentally at the lowest testing speed of 2 mm/min for each foam density and temperature of testing. Here parameters *a* and *b* include the influence of density, of direction of testing, and of temperature by having available a reference stress-strain curve at an initial strain rate and that particular temperature.

In a first step it was established that the same parameters *a* and *b* can be used on both *directions 1* and *3* for each temperature by having available the sets of experimental data. As tests are done in compression with constant crosshead speeds data was rearranged as to be able to use the ones obtained at a speed of 2 mm/min for higher speeds. The foam with density of 35 kg/m^3 showed a different behavior of the directions of testing both from the point of view of the shape of the

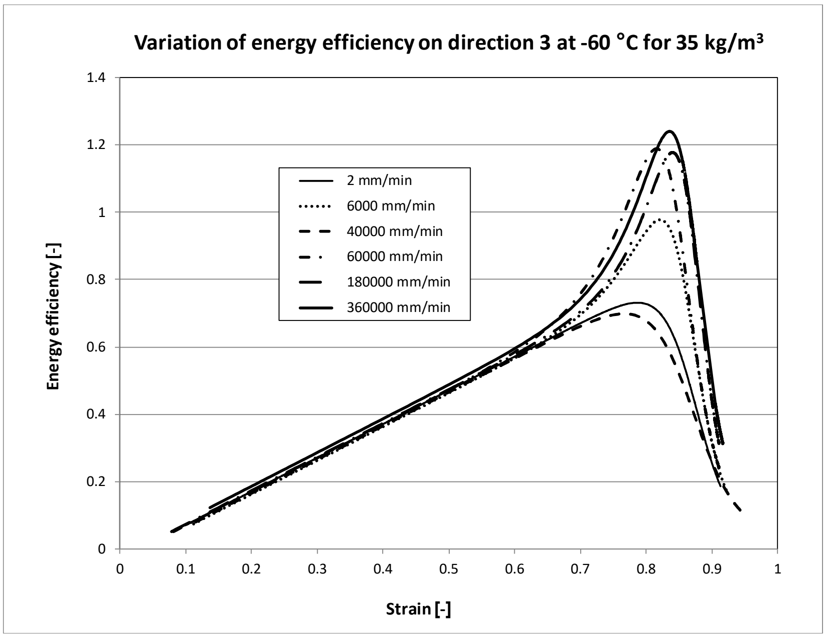
characteristic curves and the onset strain of densification. A compromise was achieved as to keep the error of the model compared to experimental data bellow 10%.
In Table 4 the parameters *a* and *b* are agiven for all three densities and temperatures of testing. For 93 kg/m^3 and 200 kg/m^3 parameter *b* is the same for all temperatures and slightly different from one density to another. Indeed, for foam with density of 35 kg/m^3 this parameter is negative for -60 ºC and positive for 23ºC and 80ºC, confirming the somehow different behavior compared to the other two foams.
Any engineering stress-strain curve determined experimentally in this work can be generated numerically by using relation (6) and the parameters *a* and *b* established as discussed.

Table 4. Values of parameters *a* and *b* as a function of density and temperature of testing.

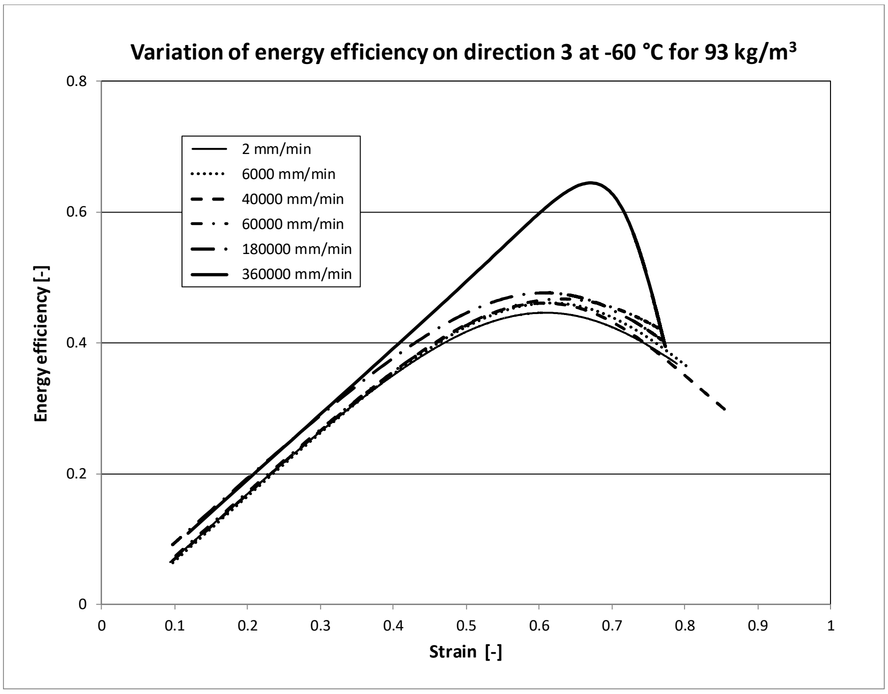
<table>
<tr><th rowspan="2">Temperature [°C]</th><th colspan="2">35 kg/m³</th><th colspan="2">93 kg/m³</th><th colspan="2">200 kg/m³</th></tr>
<tr><th>a</th><th>b</th><th>a</th><th>b</th><th>a</th><th>b</th></tr>
<tr><td>-60</td><td>0.01</td><td>-0.025</td><td>0.024</td><td rowspan="3">-0.02</td><td>0.028</td><td rowspan="3">-0.027</td></tr>
<tr><td>23</td><td rowspan="2">0.023</td><td rowspan="2">0.02</td><td>0.04</td><td>0.044</td></tr>
<tr><td>80</td><td>0.07</td><td>0.055</td></tr>
</table>

5. Variation of energy efficiency and onset of densification

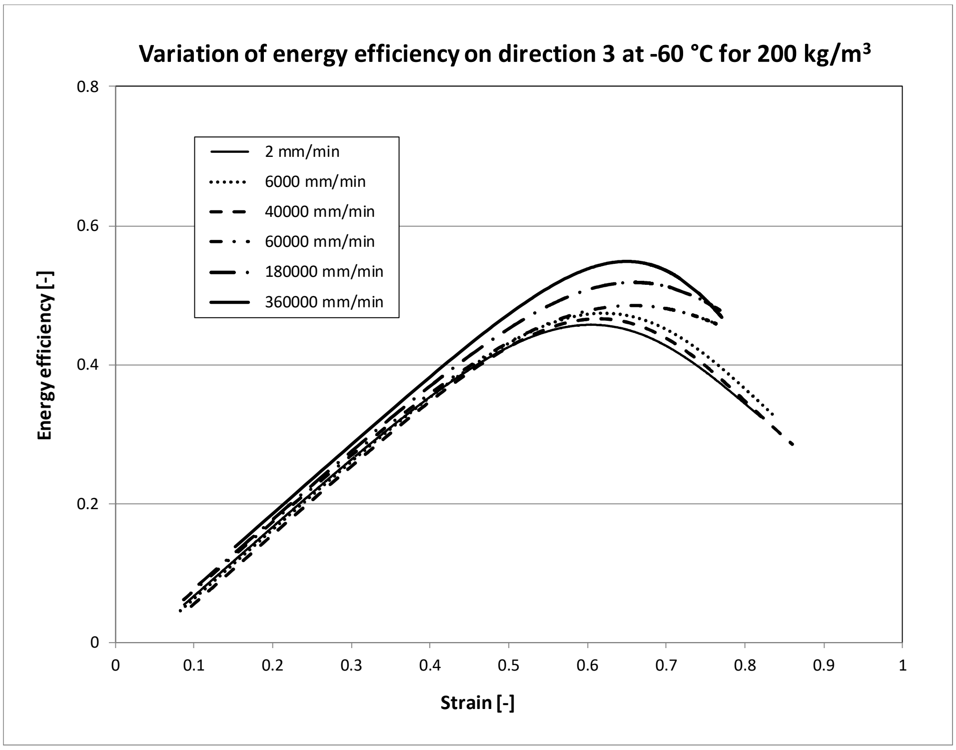
The energy absorption efficiency can be calculated by using relations (3) and (4) for all temperatures and speeds of testing. It's variation with strain attains a maximum value when the onset of densification is attained.
In Fig. 3 is presented the variation of the energy efficiency with strain for the three densities of the PUR foams at -60 ºC on *direction 3* (rise direction) under the influence of speed of testing. Fig. 3a gives the variation of energy efficiency with strain for a density of 35 kg/m^3. Regardless the speeds of testing variation is following the same linear trend up to a strain of 60%, afterwards curves part one from the other. At 40000 mm/min the curve doesn't seem to follow the general trend seen for the other speeds of testing. The maximum value of the energy efficiency increases with the speed of loading and the strain at the onset of densification increases also, from about 78% at 2 mm/min to 84% at 360000 mm/min (6 m/s), that is the increse is less than 8%.


Variation of energy efficiency on direction 3 at -60 °C for 35 kg/m³
2 mm/min
6000 mm/min
40000 mm/min
60000 mm/min
180000 mm/min
360000 mm/min
Energy efficiency [-]
Strain [-]

a)


Variation of energy efficiency on direction 3 at -60 °C for 93 kg/m³
2 mm/min
6000 mm/min
40000 mm/min
60000 mm/min
180000 mm/min
360000 mm/min
Energy efficiency [-]
Strain [-]

b)



c)

Fig. 3. Energy efficiency variation at -60 ºC: a) 35 kg/m^3; 93 kg/m^3; c) 200 kg/m^3.

For the density of 93 kg/m^3 almost all curves follow the same trend (Fig. 3b), and strain at onset of densification is about 62%. At 6 m/s the strain at onset of densification increases to 64% with a greater value of the energy efficiency. We have to mention that for speeds above 1 m/s very complicated phenomena occur and experimentally established stress-strain curves show many inertial effects even if results are filtered.

The most clear and consistent variations of energy efficiency with strain result for density 200 kg/m^3 as the increase of speed of testing results in an increase of the maximum value of the energy (Fig. 3c), and a slight increase of the onset strain of densification from 57% to almost 62% as speed of testing increases from 2 mm/min to 6 m/s.

So, on the rise direction at -60 ºC the most sensitive foam to the variation of speed of testing is the one with the density of 35 kg/m^3 with the onset of densification being produced at the highest strain. The most stable behavior in compression was obtained for density 200 kg/m^3, resulting that the onset of densification does not vary with the speed of testing. In fact it is around 62% regardless the speed of testing for both densities of 93 kg/m^3 and 200 kg/m^3.

6. Conclusions and discussion

A considerable number of tests in compression from a speed of 2 mm/min up to 6 m/s (19 speeds of testing) was performed. Experimental data were interpolated by polynomial functions on the linear and yielding regions till the beginning of the plateau region, and with exponential functions for the plateau and densification regions. A phenomenological (Nagy type) model was proposed and the engineering stress-strain curves were generated starting from a quasi-static reference curve established experimentally, which proves to be extremely useful for obtaining the response of the foam at strain rates and temperatures for which data are not available. The validation of the model was done by comparing the specific strain energy calculated with the model generated curves and the experimental ones fitted by interpolation functions. Errors were below 10%, usually very small.

Such an approach has a limited degree of generalization as the material parameters that must be established depend on the foam morphology and density. One needs, for each engineering application, reliable experimental stress-strain curves as to generate interpolation functions. However, with the help of these functions, the foam behavior from the point of view of energy absorption can be easily characterized.

For low density PUR foams speed of testing and temperature do not influence significantly the absorbed specific strain energy which is low and mostly constant. As temperature decreases the increase of speed of testing increases somehow the value of the absorbed strain energy. Only for the highest PUR foam density of 200 kg/m^3, the speed of testing, direction of testing, and temperature influence significantly the absorbed specific strain energy. The accumulated specific strain energy increases with the PUR foam density with highest values at -60 ºC for each of the three densities.

Contrary to what was expected, the tempreture and speed of testing do not influence significantly the onset of densification. The most sensitive to the influnce of this parameters is the low density foam, for which the strain at the onset of densification is between 78% and 84%.

The most stable behavior in compression was obtained for the density of 200 kg/m^3, as the onset of densification did not vary with the speed of testing. It is around 62% at -60 ºC, temperature which gave the most important variations when increasing testing speed and calculating the accumulated specific strain energy.

Acknowledgements

Both authors are grateful to Professor Gerald Pinter for facilitating the use of the MTS testing machine at the Polymer Competence Centre Leoben (PCCL), Montanuniversität of Leoben, Austria.

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