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Compression Strength and Taguchi L9 Design of Auxetic Polyurethane Foams for Rehabilitation Applications

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Auxetic foams are known to exhibit unique mechanical properties such as indentation resistance, higher pressure distribution and shear stiffness. These foams can be tailor-made, by varying the parameters used in the fabrication process, to suite different applications. In this work, Conventional or Normal PU (NPU) foams are converted to auxetic PU (APU) foams using a thermo-mechanical process. Heating temperature, compression factor and heating time are the process parameters which effects the auxeticity of the resulting foam. Taguchi L9 design methodology is used in this work to arrive at the ideal fabrication process parameters for cushioning applications. NPU foams were converted to APU foams using 9 sets of process parameters. Poisson's ratio values of these APU foams were found using digital image correlation technique and MATLAB software. Compression tests were performed for all the samples and compression strength was determined. Highest compression strength of 0.02 MPa and lowest Poisson's ratio of -0.95 were obtained. Further studies with larger samples are required to determine the ideal foam for medical cushioning applications.

Introduction

Auxetic materials are negative Poisson's ratio materials. When stretched longitudinally, normal materials contract in lateral direction. In the case of auxetic materials, when stretched longitudinally, they expand in the lateral direction showing a behavior opposite to conventional materials. Auxetic foams also exhibit higher pressure distribution [1], higher indentation resistance [2] and higher shear stiffness compared to conventional foams. The first man made auxetic foam was introduced by Lakes [3]. There are some materials in nature that exhibit auxeticity (negative Poisson's ratio effect) like cancellous bone, cow teeth skin, cat skin and silicates [4]. Auxetic materials have unusual properties like high fracture toughness [5], synclastic behavior [6] and good acoustic absorption [7]. Auxeticity can be achieved through geometric structures or by heat treatment following tri-axial compression. There are also different geometric structures which gives auxetic effect like hexagonal honeycombs, reentrant honeycombs, hexagonal reentrant honeycombs, rotating rigid structures, chiral structures, etc. [8,9].

Materials used in various rehabilitation applications such as wheelchair seat cushions, hospital beds and stump-socket interface of prosthetic limbs require unique mechanical properties that can reduce problems between skin-material interfaces. Auxetic materials can potentially be tailored for such applications. Wang et al., developed a prosthetic apparatus that uses auxetic foam layer in the socket of a prosthetic limb [10]. There is a need for development of such novel materials for rehabilitation applications which can reduce problems between skin-material interfaces. One can make auxetic foams that would exhibit the desired mechanical properties by tweaking the parameters in the fabrication process. There are various parameters which affect the fabrication process [12-14] such as temperature, pressure, time, chemistry, microstructure and additives, out of which three parameters - heating temperature, heating time and compression ratio directly affect the NPU to APU conversion process. These parameters are studied in this work. An appropriate combination of these parameters could result in foam that is ideal for cushioning application. According to Li and Zeng, even though there are many fabrication methods [11,15,16] till now there is no standardization of fabrication process [14]. It is essential to find optimum auxetic fabrication process parameters based on required application.

In this work we have applied Taguchi L9 orthogonal array to

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determine the fabrication process parameters that would give higher compression strength and lower Poisson's ratio. Taguchi method is a unique design process to economically improve performance of an operation by minimizing the number of experimental trials. It is used to achieve the best response under the studied conditions. This method allows for design of experiments using a small number of trials. Cherief et. al., used Taguchi method to study the effect of thickness of honeycomb structures on the mechanical properties of the structure [19]. Najarian et. al., used stastistical methods to study the effect of pressure, heating temperature and heating time on the auxetic conversion process [17]. Their objective was to optimize the auxetic conversion process to ensure minimal wastage of material. Gu et. al., used Taguchi design to study performance of auxetic composite structures under blast loading and developed a finite element model for the composite structure [20]. Filho et al., used Taguchi method to study auxetic rubber structures. In this work, Taguchi L9 design is used to determine process parameters to obtain APU foams with higher compression strength and lower Poisson's ratios [18].

One of the first methods describing fabrication of auxetic foams was given by Chan & Evans [11]. They described a fabrication procedure for making auxetic foams from conventional low density open-cell polymer (polyester) foams. This method of making polymeric auxetic foams involves conversion of cubical unit cells structures of conventional foam into reentrant unit cell structures. These structures have ribs that are protruding inwards. Reentrant unit cell structures are achieved by symmetrical collapse due to tri-axial compression [11]. Auxetic behavior is a result of buckling of ribs at the micro level. Parameters involved in the fabrication process such as type of foam used, heating time, heating temperature, compression ratios etc., influence the mechanical properties of the auxetic foams. This implies that auxetic foams can be tailored to exhibit required mechanical properties. Lowe and Lakes [1] studied auxetic foams for seat cushions applications and found that auxetic foams gave a better pressure distribution than conventional foams. However, they also found that the type of raw PU foam and the process parameters used in the auxetic conversion process greatly influences the end product. Li & Zeng [14] altered the fabrication process and used Styrene-acrylonitrile particles to improve load bearing and accelerate the auxetic conversion process. This shows that auxetic materials could potentially be custom made by varying the process parameters. Therefore, in this work Taguchi method is used to determine the ideal process parameters of the auxetic conversion process for cushioning applications.

Materials and Methods

Fabrication of auxetic foams

A two stage thermo-mechanical process was used for the conversion of NPU foams to APU foams. Foams of 32 gm/cc density were used. Thermo-mechanical process was applied to foams to obtain 9 samples with different conditions, i.e., heating time, heating temperature and compression factors (table 1).In the first stage of compression, the foams was squeezed inside the aluminum box of dimensions 120 x 80 x 20 mm^3 and then closed with aluminum plate by maintaining process parameters like volumetric compression factor (C.F), heating temperatures and heating time as shown in table 1. After heating the foams for the chosen amount of time, the foams are removed from the furnace and cooled for 10 minutes and then heated at the same temperature for 10 minutes. Auxetic foams are obtained after the two stage heating and cooling process.

Table 1: Taguchi orthogonal array with process parameters

Experiment number	C.F	Heating Temperature (degrees)	Heating Time (in min)
1	2	150	15+10
2	2	200	25+10
3	2	250	35+10
4	3	150	25+10
5	3	200	35+10
6	3	250	15+10
7	4	150	35+10
8	4	200	15+10
9	4	250	25+10

note: The 15+10 heating time for experiment 1 indicates that the foam is initially heated for 15 minutes at 150^{o}C and then cooled for 10 minutes and then reheated for 10 minutes at 150^{o}C. The "+10" indicates the re-heating time

Measurement of Poisson's ratio

Videos were acquired from a camera during a tension test (figure 1). The videos were converted into a series of images using Free-Studio software. A MATLAB routine was used to find the length and breadth of the samples for every image. Average Poisson's ratio values were calculated for all the converted PU foams (table 2).

Compression tests

Compression tests were performed using a static mechanical testing machine (Tinius Olsen, UK). Stress–strain curves were recorded at loading under room temperature for the nine Taguchi samples. Foams were placed between two discs and compressed with the

Table 2: Poisson's ratio values for Taguchi (T1-T9) samples

Displacement in mm	NPU	T1	T2	T3	T4	T5	T6	T7	T8	T9
5	0.25 ± 0.012	0.29 ± 0.03	0.28 ± 0.038	-0.41 ± 0.036	0.36 ± 0.03	0.34 ± 0.05	-0.92 ± 0.089	0.4 ± 0.03	0.31 ± 0.02	-0.86 ± 0.052
10	0.3 ± 0.018	0.4 ± 0.02	0.41 ± 0.025	-0.45 ± 0.019	0.49 ± 0.04	0.41 ± 0.04	-0.88 ± 0.05	0.38 ± 0.02	0.37 ± 0.015	-0.68 ± 0.04
15	0.35 ± 0.04	0.38 ± 0.027	0.42 ± 0.025	-0.38 ± 0.027	0.39 ± 0.028	0.38 ± 0.027	-0.65 ± 0.037	0.348 ± 0.03	0.4± 0.02	-0.6 ± 0.07
20	0.3 ± 0.021	0.31 ± 0.03	0.33 ± 0.021	-0.23 ± 0.02	0.38 ± 0.019	0.37 ± 0.022	-0.58 ± 0.0352	0.35 ± 0.03	0.315 ± 0.02	-0.47 ± 0.04

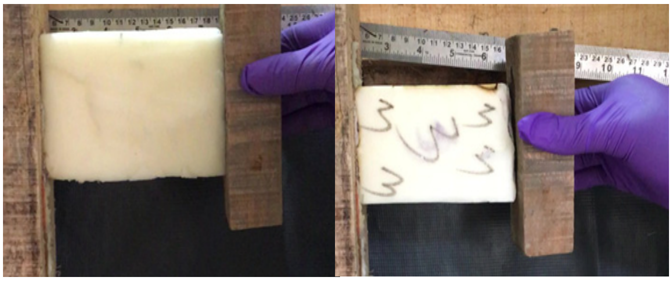

Figure 1: Tensile test of the (a) normal and (b) auxetic foams

strain rate of 1 mm/min. These tests were conducted for all the foams approximately up to 70% strains. Samples with dimensions of 50 x 50 x 20 mm^3 were used for performing compressiontests.

Taguchi experimental design:

Taguchi introduced orthogonal array for experimental design to find the optimum variables in the process. In this work, we used MINITAB 20 software for statistical analysis. As higher compression strength is required, 'larger is better' option is chosen in the software. The signal to noise ratio values for fabrication parameters of the foams were computed by MINITAB 20 using the following formula.

S/N ratio = $-10 \log_{10}(\sum_{i=1}^{n}(1/y2)/n)$

Results

Poisson's ratio results for Taguchi samples NPU and T1 to T9 foams are shown in table 2. Of the nine samples, only three samples T3, T6 and T9 were successfully converted to auxetic foams. Other foams did not show auxetic behavior. A heating temperature of 250 °C was used for the three samples - T3, T6 and T9. A lower temperature of 150°C and 200°C was used for the rest of the samples. This implies that a minimum heating temperature of 250°C must be used for conversion of the chosen NPU foam to auxetic foam. Of the three auxetic foam samples, T6 showed greater auxetic effect than T3 and T9 (Figure 2). T3 was fabricated using CF of 2 and heating time of (35+10) min. For T6, CF of 3 and heating time of (15+10) min was used. Higher CF could have caused more number of broken ribs and therefore T6 showed higher auxetic effect than T3 sample. In the case of T9, a CF of 4 was used with a heating time of (25+10) min. Although T9 has higher CF and greater heating time than T6, it showed relatively lower auxetic effect. This implies that increasing the CF beyond 3 could have an inverse effect. Therefore, for this NPU, a minimum

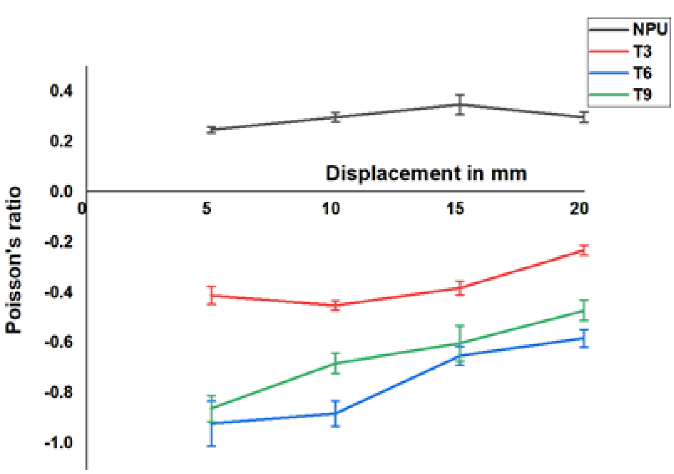

Figure 2: Poisson's ratio vs displacement plot for NPU and auxetic (T3, T6 and T9) foams

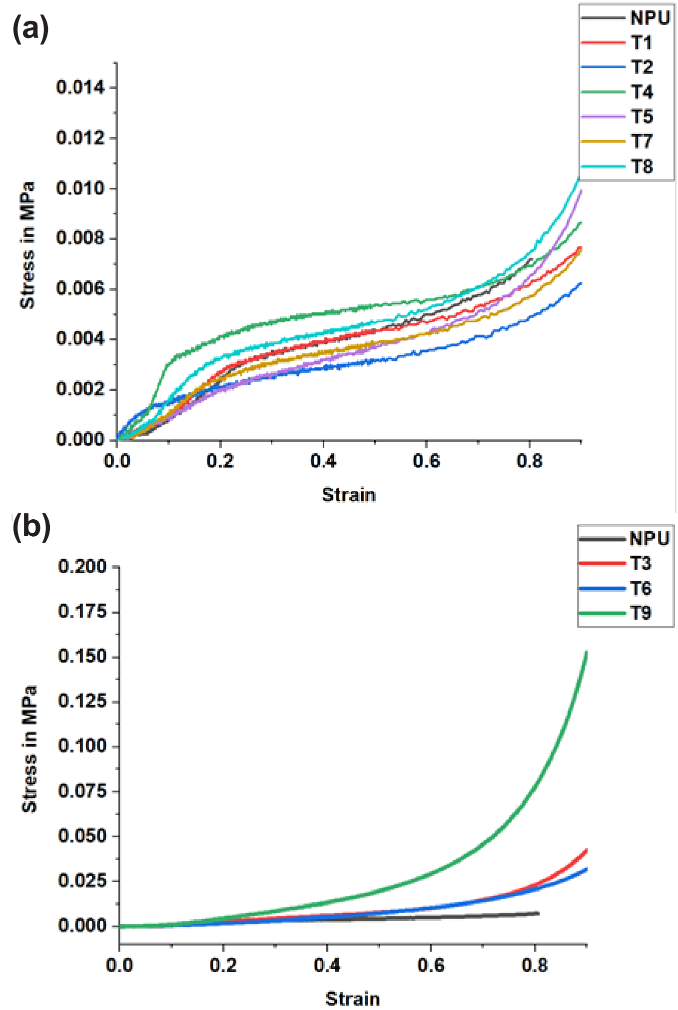

Figure 3: (a) Stress-strain curves for NPU and non-auxetic (treated) samples; (b) Stress-strain curves for NPU and auxetic (T3, T6 and T9) samples

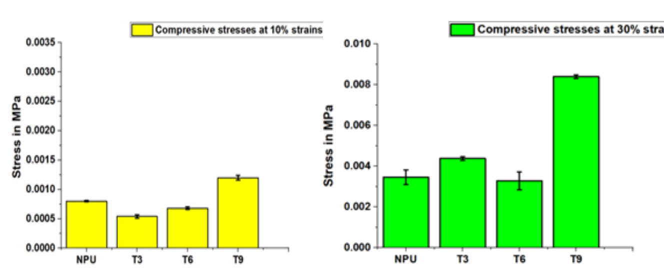

Figure 4: Compressive stress values at (a) 10% strain for NPU and auxetic (T3, T6 and T9) foams; (b) at 30% strain for NPU and auxetic (T3, T6 and T9) foams

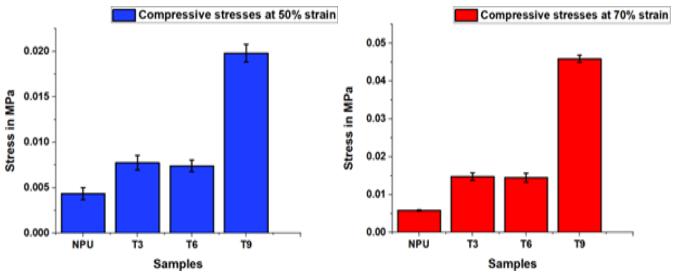

Figure 4: Compressive stress values at (c) 50% strain for NPU and auxetic (T3, T6 and T9) foams; (d) at 70% strain for NPU and auxetic (T3, T6 and T9) foams

Table 3: Response table for signal to noise ratios

Level	Compression factor	Heating temperature	Heating time
1	+43.49	+45.80	+42.13
2	+42.13	+46.14	+39.78
3	+39.44	+33.11	+43.14
Delta	4.05	13.03	3.37
Rank	2	1	3

heating temperature of 250°C and CF around 3 gives highest possible auxetic effect.

The figure 3a shows the stress-strain curves of conventional foams and samples T1, T2, T4, T5, T7 and T8. Figure 3b shows the stress-strain curves of auxetic foams T3, T6 and T9. All the foam samples that did not convert to auxetic foams showed stress-strain behavior similar to conventional PU foams i.e., NPU (figure 3a). Among auxetic foams, T9 showed highest compression strength throughout (figure 3b and figure 4). T9 samples were made with a CF of 4. The higher density of the foam could have resulted in the increase in the compression strength of the foam. T6 and T3 foam samples showed greater compressive strength than the NPU samples at higher strains (figure 4).

Compression strength values in MPa at 70 % strain were taken as a response and analyzed using statistical tool. Response table for signal to noise ratios were tabulated in tables 3 and main effects plot of SN ratios were shown in figure 5.

Discussion

While three of the nine samples showed auxetic effect, T6 was found to be ideal as it showed greater auxetic effect. Also, for the chosen foam, a minimum heating temperature of 250°C and CF of 3 are required to covert to auxetic foam using the two-stage heating process. Of the three auxetic foams, T9 showed highest compressive strength and also had auxetic behavior. T6 showed the best auxetic effect and also had higher compression strength than NPU. Therefore, both T9 and T6 could be possible candidates for use in cushioning applications. However, further studies with larger samples and standardized testing methods [21] are required to ascertain the effectiveness of the auxetic foams for rehabilitationapplications.

Figure 5: Main effect plot for SN ratios

Conclusion

This study shows that a minimum heating temperature of 250°C and compression factor of 3 are required to convert NPU to APU forms using the thermo-mechanical process of conversion. Two foams T9 (compression factor of 4 and heating time of 25+10 minutes) and T6 (compression factor of 3 and heating time of 15+10 minutes) resulted in APU foam with the best mechanical properties for cushioning applications. While T9 showed highest compression strength, T6 showed better negative Poisson's ratio.

This study was required to identify the appropriate auxetic fabrication process parameters to obtain auxetic foams with desired properties for cushioning applications. Various other parameters such as the composition of the raw foam used for fabrication, additives such as silver nano particles, styrene acrylo nitrile particles [14], etc., used during synthesis of the raw foam can also influence the behavior/ properties of the auxetic foam. Experimental studies with larger foam samples mimicking the seating mechanics [21] can ascertain the ideal properties required of the foams. Simulation studies [22] can also be used to understand the behavior of various foams in cushioning applications.

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