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Single point incremental forming of shape memory polymer foam

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Abstract. In this study single point incremental forming of shape memory foam is investigated. The shape memory effect makes the foam an attractive material for the fabrication of recoverable components such as reusable dies for low pressure forming processes. The mechanical properties of the polymer have been investigated by means of tensile testing at elevated temperature. The maximum achievable formability for this material for single point incremental forming has been characterized both at room and elevated temperature. After an explorative study on simple benchmark cases, heat assisted single point incremental forming has been used to study the possibility of manufacturing a recoverable die for custom-made orthopaedic shoe insoles.

1. Introduction

The growing desire of consumers to distinct themselves from others as well as the large demand for custom orthosis dictate the increasing need for mass personalisation. The development of flexible production processes, accompanied by cheap reconfigurable tooling, is therefore essential. This study explores the potential of using Shape Memory Polymers (SMPs) as base material for the fabrication of reconfigurable and reusable dies for low pressure forming processes. SMPs are a class of polymers that have the ability to recover their original shape in response to stimuli (electricity, heat, pH, ultraviolet light and magnetic field) [1]. This recovery allows reusing the material and therefore eliminating material waste. Using Single Point Incremental Forming (SPIF), shape memory foam can be compressed and formed in a wide variety of geometries. SPIF is a well-known flexible forming process for metal sheets, where a sheet is formed in a stepwise fashion by a hemispherical tipped tool progressing along a set of subsequent contours [2]. However, limited knowledge exists about processing highly compressible foams by SPIF.

The first section of this study focusses on the characterisation of the thermo-mechanical properties of SMP foam by compression and tensile testing. The second section deals with the formability of SMP

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Table 1. SMP foam and polyurethane (PU) properties.

Property	Unit	Value
Cell size of the foam	μm	+/−700
Density of the foam (ρ^*)	kg/m^3	45
Density of the polyurethane, rigid (ρ_s) [1]	kg/m^3	1200
Thermal conductivity of the foam	W/m*K	0.0334
Thermal conductivity for foam after 20% compression	W/m*K	0.0334
Thermal conductivity for foam after 50% compression	W/m*K	0.0335
Glass transformation temperature of the foam (Tg)	°C	72
Young's modulus of the polyurethane (E_s) [1]	Mpa	1600
Yield strength of polyurethane, rigid (σ_{ys}) [1]	Mpa	127

foam in the SPIF process both at room and elevated temperatures. The geometrical accuracy of the part has been measured with a laser line scanner. Finally an exploratory study was performed to determine the possibility of making a reusable SMP foam die for custom-made orthopaedic shoe insoles.

2. Experimental procedure

2.1 Material

The material used for all experiments was a closed-cell polyurethane-SMP foam (SmartRec 7001: produced by Recticel Company). To make open- or closed-cell foams, gas bubbles can be formed by forcing physical blowing agents into liquid monomer or hot polymer [3]. Compared to fully dense shape memory polymers (SMPs), SMP foams can withstand higher deformations and show extremely high volume recovery ratios [1]. Generally, SMP foams are cheaper and lighter than conventional shape memory alloys and have special characteristics such as excellent biocompatibility and heat insulating properties. This material exhibits thermally actuated shape memory behaviour and can easily be cut in any size. For SPIF process the foam was cut into a square shape with dimensions of 225 mm × 225. The properties of the foam as well as the cell-wall material (polyurethane) are presented in Table 1.

2.2 Free recovery test

To study the temperature dependent compressibility and the shape recovery of the foam, a static load of 0.8 kg was placed on top of a foam block with a size of 35 × 35 mm^2, and a thickness of 11 mm (see Fig. 1). Afterwards, the loaded foam was placed inside a furnace, heated to respectively 50 °C, 65 °C, 80 °C, 100 °C, 120 °C, 140 °C, 160 °C, 170 °C, and 175 °C and held for 2 minutes. The core temperature of the foam was monitored by means of a K type thermocouple. Subsequently, the samples were unloaded, air cooled and the thickness reduction was measured at different temperatures. Figure 1b shows the results of the compression test at different forming temperatures. The compressibility of the foam increases with increasing temperature and a maximum engineering strain of about 82% was achieved at 174 °C. A free recovery test, consisting of heating the unloaded deformed samples above the glass transition temperature of 72 °C, yielded a full recovery for all observed samples.

2.3 Compression and tensile test

Plastic foams under compression show three different regions: linear elasticity, plastic collapse and densification. In the linear elasticity region cell face stretching occurs, in the so-called plateau region

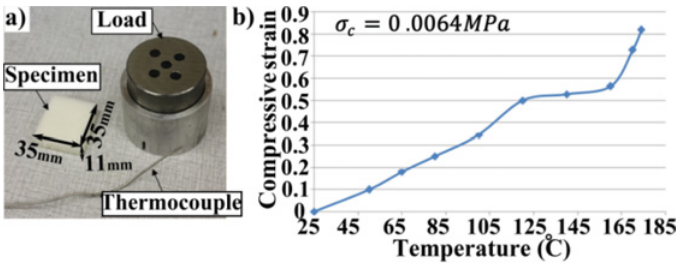

Figure 1. a) Free recovery test and b) compressive strain versus temperature, σ_c is the compressive stress applied on the surface of the foam.

the plastic collapse occurs by formation of plastic hinges, and in the densification region, large plastic strain in compression crushes the cell walls together [3]. These boundaries are defined for the presented SMP foam using Eqs. (1) and (2) and the data given in Table 1. The boundary between the linear-elastic zone and that of plastic collapse is given by [3]:

$$\sigma^* = \frac{0.0081(\sigma_{ys})^4}{(E_s\varepsilon)^3} \cdot \tag{1}$$

In which σ_{ys}, E_s, and ε are yield strength, elastic modulus of the PU and compressive strain respectively. The boundary between the plastic collapse and densification regions is given by [1]:

$$\sigma^* = 0.11187(0.9475 - \epsilon)\sigma_{ys}(1 - \varepsilon_c)^{\frac{1}{2}}(1 + 2.33\varepsilon_c) \tag{2}$$

ε_c is a limiting strain for densification.

$$\varepsilon_c = 1 - 2\frac{\rho^*}{\rho_s} \tag{3}$$

in which ρ^* and ρ_s are density of the foam and polyurethane respectively. This foam has a small relative density (i.e. $\frac{\rho^*}{\rho_s} = 0.0375$), this reduces the plateau stress and increases the strain at which densification occurs (i.e. $\varepsilon_c = 0.925$).

Compression tests at elevated temperature show that the plastic collapse strength decreases linearly with an increasing forming temperature up to Tg and the formability of the foam under compression enhances at elevated temperature [3].

As a test standard for tensile testing of flexible cellular polyurethane foam, ASTM D3574 (Test E) [4] was used to determine the tensile properties. The tests were conducted at a crosshead speed of 2 mm/min and temperature range of 25 °C – 140 °C. A universal testing machine, Instron 5985, equipped with a heating chamber was used. The temperature range has been selected in a way that it covers temperatures below and above the glass transformation temperature. The stress-strain curves obtained by the tensile tests are shown in Fig. 2b. It is observed that the tensile stress of the foam increases with deformation. In contrast to metals, in which strain hardening occurs due to dislocation movements and entanglement, the main cause of the hardening in SMP foam is the compression of the cell gas [5]. Upon plastic deformation the cell walls in the SMP foam turn towards the tensile axis, creating a yield point [3]. By heating the foam the yield strength drops, also the maximum elongation increases with increasing temperature up to Tg. However, both elongation and yield strength of the foam decrease upon heating the foam above its Tg. The reduction in the elongation above Tg might be due to the shape recovery of the foam or weakening of the cell wall.

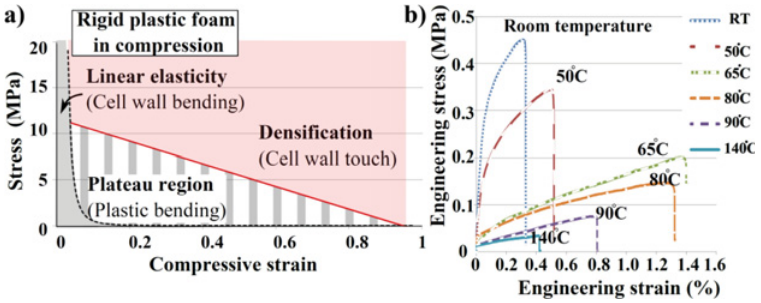

Figure 2. a) Compressive stress-strain for SMP foam b) Tensile test curves at different temperatures.

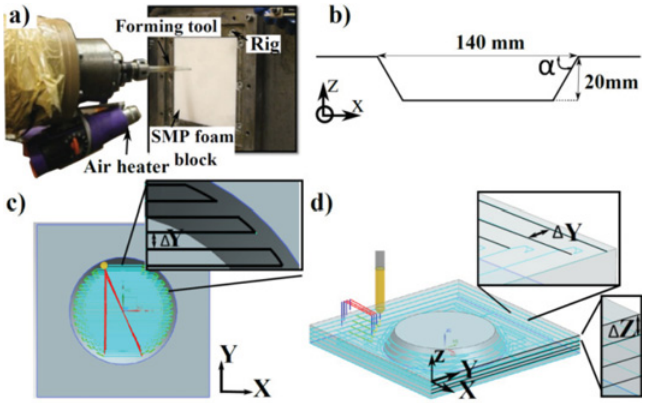

Figure 3. a) Warm forming set-up, b) truncated cone specification for formability tests, c) cavity mill tool path with "Zig Zag" cut pattern for forming SMP foam in sheet and d) with "follow periphery" cut pattern for forming SMP in block form. For all experiments a constant step-over (ΔY) of 10 mm, a step-down (ΔZ) 0.5 mm, a tool size of 10 mm and a forming speed of 2 m/min were selected.

3. Experimental plan

The feasibility to process the shape memory polymer foam by using SPIF was determined by its maximum formability and achievable accuracy. The geometry studied for both formability and accuracy evaluations consists of a truncated cone with a major base of 140 mm and a depth of 20 mm (see Fig. 3b). In order to investigate the influence of the part rigidity on the forming mechanism, the tests were performed both on a sheet of 11 mm thick and a block of 50 mm thick. The sheet foam was only supported around its periphery and the test consisted of forming the negative cone shape by a zig-zag planner pattern of the tool inside the cone's cavity (see Fig. 3c). The block foam was supported throughout the entire backside and the corresponding test consisted of forming the positive cone shape by a planar pattern following the periphery of the cone concentrically (see Fig. 3d).

As thermomechanical tests show that forming the foam close to its Tg can improve the formability, tests were performed both at room temperature and at 65 °C, measured by the thermocouple attached to the surface of the foam. The warm forming temperature should be kept below its Tg to prevent shape recovery. For the warm forming tests the sheet and block foams were heated by an air heater moving with the forming tool (see Fig. 3a). Moreover, the backside of the sheet foam was heated by a stationary air heater positioned at the backside of the sheet to increase the temperature homogeneity through the thickness of the sheet. The formability in this process is studied through making a series of cones while

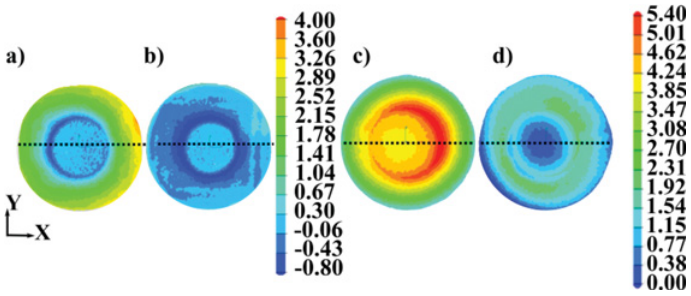

Figure 4. Colour plot representing dimensional accuracy (in mm) in comparison to the CAD surface of a) warm formed SPIF formed block (20° cone), b) compensated formed block, c) warmed formed SPIF formed sheet (15° cone), and d) compensated formed sheet.

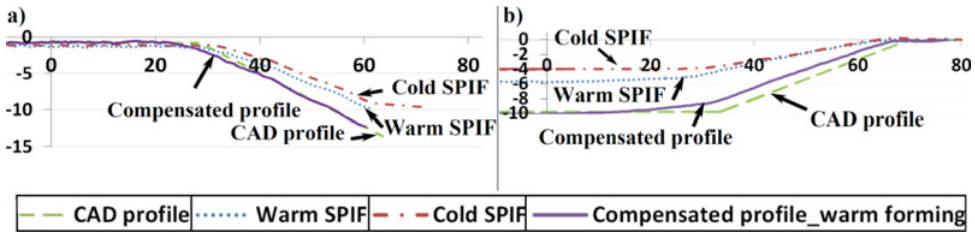

Figure 5. Accuracy comparison along the cross-section parallel to the X axis shown on Fig. 4 a) block (20° cone), and b) sheet (15° cone).

subsequently increasing the wall angle (α). The maximum forming angle was defined by identifying the maximum wall angle (α) at which no material failure can be observed, a resolution of 1° was chosen for this maximum wall angle determination. The geometrical accuracy of the SPIF forms parts has been measured with a laser line scanner.

4. Experimental observations

The maximum nominal forming angle at room temperature for the sheet and block were determined to be 25° and 26° respectively. However, in the sheet foam the material failure occurred at the backside, whereas in the block foam the cracks were located in the tool side of the foam showing a difference in the deformation mechanism. The deformation in a block consists mainly of a compression in Z direction while the sheet foam shows some rigid body deformation during SPIF process as it is not supported from the back. This leads to tensile stresses on the back of the sheet foam. The formability of the foam has been found to improve considerably at the elevated temperature (~ 65 °C) where the nominal forming angle for both sheet and block foams were determined to be 32°. The accuracy results for a block show a large amount of springback on the wall (see Figs. 4a and 5a) and for the sheet foam severe undeforming in the cone wall and the bottom region is observed (see Fig. 4c and Fig. 5b). Unlike metals which typically show inwards bulging of the bottom in shallow sloped Single Point Incrementally (SPIF) parts, the bottom of the SPIF formed sheet/block foam is horizontal and the cone wall is straight. The accuracy can be improved through iterative toolpath compensation, as is shown in Fig. 4b and d. From the accuracy plots and Fig. 5 it can be concluded that the accuracy can improve significantly after a simple mirroring toolpath compensation [2].

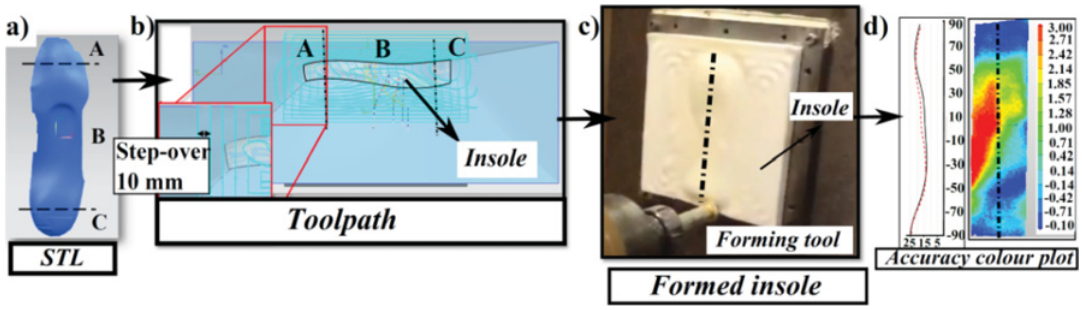

Figure 6. a) Corrected insole STL, b) Tool path generation for scanned insole, c) SPIF of insole, and d) accuracy measurements (left picture shows accuracy profile along dashed line).

5. Shoe insole manufacturing case study

Traditional methods for making custom insoles, such as wrapping a wet plaster around the feet for creating a negative plaster cast, which can later be used for fabrication of individual positive plaster molds, are cumbersome and time-consuming. The desired foot corrections applied to the casts of the foot made by these methods are applied manually, resulting in limited geometrical accuracy of the manufactured insole, and are highly dependent on the skills of the involved technician. Alternatively SPIF as a numerically controlled dieless forming process can be used for forming recoverable dies for custom-made orthopaedic shoe insoles. Generally this can be done in two different ways. In the first method the patient's foot is scanned and the desired corrections on the STL file can be made by the specialist using commercially available orthotic design software. Afterwards, a corrected STL file is imported to the CAD/CAM software and a toolpath can be generated for incremental forming of the SMP foams into moulds for the insole. Later, the foam can be heated above its Tg to achieve a flat block and the process can be repeated without loss of material. The second method starts by pressing the patient's foot into an SMP foam block, scanning the footprint, correcting the toolpath to the desired shape and modifying the already deformed footprint geometry by SPIF. Furthermore, localized shape recovery is possible on the deformed foam at the desired regions; this can be achieved by locally heating up the foam above its Tg.

The first method, as described above, has been utilised as a case study. Figure 6 shows the summary of the manufacturing process. The corrected STL file of the scanned insole is imported to a commercial CAD/CAM software. A "cavity mill" tool path (see Fig. 3C and Fig. 6b) is used for manufacturing an insole in a block of 30 mm (see Fig. 6c), after which the accuracy of the part is measured using a laser line scanner (see Fig. 6d). It is observed that the insole geometry could be successfully formed inside the foam block. However, further studies using toolpath compensation strategies are required to improve the accuracy of this part.

6. Conclusion

This study showed the possibility of manufacturing recoverable shallow sloped parts using SMP foam. It has been observed that forming at elevated temperature increases the formability by 28%. This process has the potential to manufacture custom-made reusable dies from SMP foams. Orthotic insoles were evaluated as possible application as their typical geometry lies within the process window for incrementally formed SMP foam.

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