Single Point Incremental Forming of Polymers

Tânia A. F. Marques
Instituto Superior Técnico, T. U. Lisbon, Portugal
E-mail: taniaafm47@gmail.com

Abstract

The actual need of the constant introduction of new products in the market leads to the development of agile manufacturing techniques. Single point incremental forming (SPIF) is a new innovative and feasible solution for the rapid prototyping and the manufacturing of small batch sheet parts. The process is carried out at room temperature (cold forming) and requires a CNC machining centre, a hemispherical tip tool and a simple support to fix the sheet being formed.

The aim of this research focuses on the determination and experimental validation of the formability limits, evaluating the incremental forming application potential.

In order to fulfill the aforementioned objectives four different polymers were selected and independent calibration of physical, mechanical properties and formability limits were performed under laboratory controlled conditions.

The study allows the confirmation that SPIF can be successfully extended to polymers.

Keywords: Single Point Incremental Forming, Polymers, Mechanical Characterization, Formability Limits, Experimentation.

1. Introduction

Conventional processing technologies for polymer materials require large batch sizes (mass production) and are based on heating-shaping-cooling manufacturing routes, because the energy costs and the capital investment in equipment and tooling (i.e. machine-tools, moulds, dies, jigs and fixtures) are very high, these technologies are not appropriate for small batches and prototypes. The actual market demands of decreased life-cycles, development and production lead times, creates a necessity for developing flexible production techniques to allow a cost-efficient small-batch production of polymer parts.

In a recent paper Franzen et al. (2008) presented the first breakthrough towards the development of an innovative cold polymer processing technique for flexible small-batch production and rapid prototyping through the evaluation of the performance of commercial Polyvinylchloride (PVC) sheets in single point incremental forming (SPIF) applications. The two major contributions of the paper were the identification of the major operating parameters and the characterization of the formability limits of the process. Three different failure modes were identified and special emphasis was placed on the experimentally observed phenomena that are different from those commonly seen in the SPIF of
In a subsequent paper Le et al. (2008) published a preliminary set of experimental results for the SPIF of Polypropylene (PP) sheets. The research work plan was built upon statistical analysis based on design of experiments and comprised the study of the influence of the step size, tool size, feed rate and spindle speed on the overall formability of PP sheets with 3 mm initial thickness. Two failure modes similar to those previously observed by Franzen et al. (2008) in PVC were reported.

In a second paper, Martins et al. (2009) extended the scope of their investigation to include four additional polymers, namely Polyoxymethylene (POM), Polyethylene High Density (PE), Polyamide (PA) and Polycarbonate (PC). The previously identified failure modes were revisited and systematized in the light of new experimental data. A first attempt was made towards the development of criteria for the selection of polymers for SPIF applications.

Silva et al. (2010) proposed a theoretical framework for SPIF of polymers, starting from the theoretical framework for SPIF of metals that was developed before (Silva, 2008a), and the new contribution to knowledge is related to the innovative extension of the model to pressure-sensitive yield surfaces that are typical of the cold forming of polymers. Results show that PVC add new phenomena in the characterization of the formability limits in SPIF by introducing new modes of failure that are not experimentally observed in metals. The observations of crack opening along the circumferential direction at the transition zone between the inclined wall and the corner radius of the parts reveals that fracture is not preceded by localized necking and that crack propagates under tensile meridional stresses acting under stretching modes of deformation. These results are similar to those found by Silva et al. (2008a, 2008b) in case of the SPIF of metals.

This work extends the formability limits to three additional polymers characterized by different chemical, physical and mechanical properties, and confirmed the PVC formability limit. Including a preliminary application of the Polyethylene terephthalate (PET) polymer.

2. Experimentation

This section starts by presenting the results of the materials characterization tests, the formability limits for the four polymers and describes the tool set-up and the experimental procedure utilized for producing polymer parts with the SPIF process.

2.1 Material characterization

The mechanical characterization is performed on commercial polymer sheet blanks having a uniform thickness profile of 2 mm. Four different thermoplastics are used: polyamide (PA), polycarbonate (PC), Polyethylene terephthalate (PET), and polyvinyl chloride (PVC).

Mechanical properties of the polymeric materials are obtained by means of tensile tests, bi-axial circular (50 mm) and elliptical (100/63 mm) hydraulic bulge tests, fracture toughness tests and density measurements. The tensile and the fracture toughness tests are performed in a mechanical testing machine, while the hydraulic bulge tests are performed in a universal sheet metal testing machine, finally the density measurements are performed in a precision balance equipped with a density
measurement kit. Table 1 summarizes the average results of the mechanical properties of the polymers.

**Table 1 - Representative summary of the mechanical properties of the polymers.**

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Elasticity Modulus $E$ [MPa]</th>
<th>Yield Stress at tensile $\sigma_Y$ [MPa]</th>
<th>Effective strain at fracture (tensile test)</th>
<th>Effective strain at fracture (bulge test)</th>
<th>Fracture Toughness $R$ [kJ/m$^2$]</th>
<th>Density [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td>927.9</td>
<td>36.04</td>
<td>1.08</td>
<td>1.37</td>
<td>22.23</td>
<td>1.14</td>
</tr>
<tr>
<td>PC</td>
<td>2457.7</td>
<td>34.40</td>
<td>0.68</td>
<td>0.70</td>
<td>25.92</td>
<td>1.19</td>
</tr>
<tr>
<td>PET</td>
<td>2661.9</td>
<td>46.11</td>
<td>0.09</td>
<td>1.38</td>
<td>17.98</td>
<td>1.33</td>
</tr>
<tr>
<td>PVC</td>
<td>3491.9</td>
<td>34.50</td>
<td>0.49</td>
<td>0.80</td>
<td>23.17</td>
<td>1.43</td>
</tr>
</tbody>
</table>

The effective stress-strain curves obtained from the tensile and the bulge tests are presented in Figure 1.

Figure 1 Effective stress-strain curves of PA, PC, PET and PVC obtain of tensile and bulge tests.

The PET material presents for the tensile tests the smaller value of strain, because fracture is preceded by localized necking, that does not propagates in the length of the specimen like the other polymeric materials in this study (Figure 1).

### 2.2 Fracture Forming Limits

Formability of the polymer sheet blanks were evaluated by means of tensile tests and bi-axial circular (50 mm) and elliptical (100/63 mm) hydraulic bulge tests. The tensile tests were performed in a mechanical testing machine while the hydraulic bulge tests were performed in a universal sheet metal testing machine.

The determination of the forming limit curve, FLC, was constructed by taking the principal strains at failure from etched grid-elements placed just outside the neck. And the experimental determination of the fracture forming limit line, FFL, requires measuring the thickness and width at fracture.
The FLC and FFL measured strains had the same magnitude, so FFL’s should be employed. The FFL’s obtained can be approximated by straight lines and are plotted in Figure 2.

![Figure 2 – Fracture Forming Limit Lines of PA, PC, PET and PVC.](image)

In the PA bulge specimens occurred elastic recovery in the fracture area, so the experimental measurements of the thickness and width were not possible in the fractured specimens. Although, some bulge specimens were stopped before fracture, making possible measurements, and the determination of the fracture forming limit line. Thus, the PA fracture forming limit line is undersized.

### 2.3 Tool set-up and experimental work plan

The capability study of using commercial polymer sheets to produce SPIF parts was performed in a Deckel Maho CNC machining centre equipped with a tool set-up comprising the following components: (i) a blankholder, (ii) a backing plate and (iii) a single point forming tool (Figure 3).

![Figure 3 (a) Schematic representation of the SPIF process. (b) Tool set-up.](image)

The blankholder is used for clamping and holding the polymer sheet in position during SPIF. The backing plate supports the sheet and its opening defines the working area of the single point forming tool. The single point forming tool has a spherical end and is utilized to progressively shape the sheet.
into a component. The tool path is controlled by the CNC machining centre and during the forming process there is no backup die supporting the back surface of the polymer sheet.

The experiments were performed in a benchmark truncated conical shape characterized by increasing the drawing angle $\Psi$ with the depth (Figure 4) and the maximum drawing angle $\Psi_{\text{max}}$ was obtained from measuring the depth of the specimen at fracture.

![Figure 4 Geometrical details of the formability test performed on a truncated hyperboloid shape with an initial diameter of 160 mm and initial drawing angle, $\Psi_0$, continued with an increasing angle, $\Psi(h)$, with the depth.](image)

Three different single point forming tools with hemispherical tips and diameters of 8 mm, 10 mm and 12 mm were used in the experiments. The tool path is helical, with a step size per revolution equal to 0.1 mm and a feed rate of 1000 mm/min, generated with the computer aided manufacturing (CAD/CAM) commercial software Mastercam. The lubricant applied between the forming tool and the polymer sheet was a water-soap emulsion.

The experiments were designed to validate the formability limits determined by tensile and bulge tests and to isolate the influence of the most relevant process parameters: (i) thickness of the sheet, (ii) diameter of the single point forming tool, and (iii) initial drawing angle.

### Table 2: Work plan.

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial drawing angle, $\Psi_0$ (º)</th>
<th>Tool diameter (mm)</th>
<th>Thickness of the sheet (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA, PC, PVC</td>
<td>30</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>PET</td>
<td>30</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

The SPIF tests were performed in a benchmark truncated hyperboloid shape characterized by a continuously increasing drawing angle $\Psi$ with the depth (Figure 4). The maximum drawing angle was obtained from measuring the depth of the tool path at failure. Initially some exploratorium tests were
performed, and showed that the PET was the material with best behaviour of the four tested materials, thus the following work plan presented in Table 2 is performed.

3. Results and discussion

On the contrary to metals where formability in SPIF is mainly influenced by the thickness of the sheet, the diameter of the forming tool and the ductility of the material, polymers may also show dependency on the initial value of the drawing angle, \( \Psi_0 \). Thus, the analysis of the density measurements, formability by means of the maximum drawing angle and fracture forming limits, and the thickness variation are presented.

In what concerns the appearance of PVC sheet parts reveals the occurrence of “stress whitening” due to crazing mechanism. Because crazing is essentially related to the formation of a network of microvoids in the PVC matrix it must be accompanied by a significant and progressive reduction of density. In fact, density measurements performed, show that density is progressively reduced up to a maximum value near the crack compared with a non deformed area, like in Franzen et al. (2008) and Silva et al. (2010) research. This behaviour is different from that presented by SPIF parts made of PA, PET and PC in which variation of density is not significant.

The experimental results included in Figure 5 show the influence of the diameter of the single point forming tool on the maximum drawing angle for PC, PET and PVC. In the PA sheets twisting occurred, and the tests were stopped before fracture, thus the results for PA are not representative of the material behavior.

![Figure 5 Maximum drawing angle, \( \Psi_{max} \), as a function of the tool diameter for sheet blanks with 2 and 3 mm thickness, and initial drawing angle of 30°.](image)

For the PC sheets formability increases when the diameter tool increases. And the maximum drawing angle reduces with the increase of blank thickness, opposing the results of Martins et al. (2009). In fact the 3 mm initial thickness parts showed surface damage due to galling, see Figure 6.

PVC sheets results are inconclusive, and the values for sheets with 3 mm initial thickness are different
from that commonly found in Franzen et al. (2008) and Silva et al. (2010). This may be due to the difference of roughness in the two surfaces of a sheet, and the grid etching did not take this into account, thus in the 3 mm initial thickness blanks the tool actuated in the surface with more roughness leading to a lower formability.

Figure 6 Detail of the poor surface quality due to galling.

The PET blanks showed the best formability from all the materials, none of the parts produced with a 30° initial drawing angle fractured, reaching the maximum drawing angle of the geometry, 90°.

In Figure 7 is presented the results for the strain measurements for the PA SPIF parts, when initial thickness of the blank is 3 mm, with an initial drawing angle of 30°.

Figure 7 Experimental strains obtained in the SPIF of 3 mm PA parts ($\Psi_0 = 30^\circ$).

For the parts produced with tool diameter of 8 and 10 mm the strain level is higher than the FFL, this may be due to the problems found in the FFL determination in PA. Although, the deformation changed from plane strain condition to bi-axial stretching, this may be due to the twisting observed in all the PA parts.

Figure 8 presents the results for the strain measurements for the PC SPIF parts, when initial thickness of the blank is 2 mm, with an initial drawing angle of 30°. The results show the good agreement between the experimental strains at failure and the FFL determined by means of tensile and bulge tests.
Figure 8 Experimental strains obtained in the SPIF of 2 mm PC parts ($\Psi_0 = 30^\circ$).

Figure 9 presents the results for the strain measurements for the PVC SPIF parts, when initial thickness of the blank is 3 mm, with an initial drawing angle of 30º. The results show the good agreement between the experimental strains at failure and the FFL determined by means of tensile and bulge tests.

Formability is not very sensitive to the increase of the tool diameter, opposing Franzen et al. (2009) and Silva et al. (2010). This result may be due to the small variation in the tool diameter in this study (8, 10 and 12 mm) when compared with the values utilized by other works (10 and 15 mm).

Figure 10 presents the results for the strain measurements for the PET SPIF parts, when initial thickness of the blank is 2 mm, with an initial drawing angle of 30, 45 and 60º.
Figure 10: Experimental strains obtained in the SPIF of 3 mm PVC parts ($\Psi_0 = 30, 45$ and $60^\circ$ and $\Theta_{tool} = 8$ mm). Facture only occurred for the part produced with an initial drawing angle of $60^\circ$, reaching a maximum drawing angle of $84^\circ$. Thus, the influence of the initial drawing angle is relevant, so when the initial drawing angle increases the formability decreases. In the PET parts, fracture only occurred when the initial drawing angle was $60^\circ$, thus all the other parts reached the maximum drawing angle of the geometry, $90^\circ$. The results show the good agreement between the experimental strains at failure and the FFL determined by means of tensile and bulge tests.

The evolution of the wall thickness along the meridional cross section of truncated conical shapes was evaluated and compared with the values obtained by the sine law (Figure 11). It shows the ability to model the resulting wall thickness along the inclined surface of the SPIF parts for polymer parts as well.

Figure 11: Experimental variation of the thickness with the drawing angle along the meridional cross section of a truncated conical shape with varying drawing angles, $\Psi$ (initial thickness of 2 mm, diameter tool of 8 mm and initial drawing angle of $30^\circ$).
5. Conclusions

This work extends the pioneer work in the field of the formability limits in single point incremental forming of polymer sheet blanks, that was exclusively performed on PVC (Silva, 2010), to three other types of polymers with different chemical, physical and mechanical properties. Including a preliminary application of the Polyethylene terephthalate (PET) polymer in SPIF.

Experimentation in SPIF showed that PET provides the best formability of all the polymers tested. PA has also good formability if twisting can be prevented, PVC provides the best resistance to springback, and Polycarbonate (PC) presents the key feature of keeping transparency after being plastically deformed.

The results show the good agreement between the experimental strains at failure for PC, PET and PVC and the FFL determined by means of tensile and bulge tests.

References


