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Single point incremental forming of polymers

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ABSTRACT

The aim of the present paper is to evaluate the possibility of producing low-cost, small-batch, polymer sheet components by means of single point incremental forming (SPIF) at room temperature. During the research work, five different thermoplastic materials were incrementally formed into cones with an increasing wall angle on a conventional CNC milling machine. In designed experiments, significant process parameters were found, and influential material properties were identified. The experimental results confirm that SPIF of commercial polymer sheets at room temperature has potential for the manufacture of complex parts with very high depths.

1. Introduction

Conventional technologies for producing polymer parts are based on heating-shaping-cooling manufacturing routes and are closely linked to mass production due to economic limitations. To meet the demands of decreased life-cycles, short development and production lead times and to allow a cost-efficient small-batch production of polymer parts, flexible production techniques are necessary.

With a similar motivation for metals, a new sheet metal forming process was developed within the past years, called single point incremental forming (SPIF) [1].

Extending the scope of application to other materials than metals, the first breakthrough was recently performed by Franzen et al. [2], who showed that SPIF can be successfully utilized for producing sheet parts made of polyvinylchloride (PVC). Conical parts with a continuously increasing wall angle ψ, were manufactured with a conventional SPIF set-up (Fig. 1).

Le et al. [3] published a preliminary set of experimental results for the SPIF of PP (polypropylene). The research work plan was built upon design of experiments (DoE) and comprised the study of the influence of 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. [2] in PVC, were reported.

Franzen et al. [4] extended the scope of their investigation including four additional polymers. They investigated the effect of the initial drawing angle on the formability. It is shown that the variation in color, which is observed especially in PVC, can be related to the variation in density, derived from the development of crazes.

Taking into account the above described state-of-the-art, the focus of the current paper is twofold: (i) determination of process limits and (ii) evaluation of product properties. Fracture forming limit diagrams are introduced to determine formability. Accuracy and color variations of SPIF parts are comprehensively evaluated.

Five different polymers, polyoxymethylene—POM, polyethylene—PE, polyamide—PA, polyvinylchloride—PVC and polycarbonate—PC, with material structures varying from high-crystalline (POM) to amorphous (PC), were investigated in this paper. The first part focuses on the material characterization introducing a fracture forming limit diagram for PVC. After that, the formability of truncated conical shapes with a continuously increasing wall angle is analyzed by means of experiments, and, finally, material evaluation criteria are introduced.

2. Material characterization

The yield stress σ_Y and the modulus of elasticity E of the polymers were determined by means of tensile tests. The specimens were machined in accordance with the ASTM D 638 norm. The testing speed was set to 50 mm/min. The density of the polymers was measured utilizing a pyknometer. Fracture toughness R was evaluated from tensile tests performed on double-edge notched (DEN) specimens (Fig. 2). The approach considers the total work of fracture W_t to be broken down into two distinctive components

$$W_t = W_p + W_f \tag{1}$$

the energy W_p absorbed by the plastically deforming region and the energy W_f related to the creation of new surfaces. W_f is also known as the 'essential work of fracture' [5]. Fracture toughness R is computed from the specific essential work of fracture $w_f = W_f/at$ under limiting conditions of the length of the ligament a being equal to zero with t as the sheet thickness.

The formability of the polymer sheets was evaluated by means of tensile tests and bi-axial circular (Ø 100 mm) and elliptical (Ø$_{\mathrm{major}}$ 100; Ø$_{\mathrm{minor}}$ 63 mm) hydraulic bulge tests (Fig. 3).

In case of PVC, experimental observations revealed that neck formation is suppressed in hydraulic bulge tests so that traditional forming limit diagrams (FLDs) are inapplicable to describe failure.

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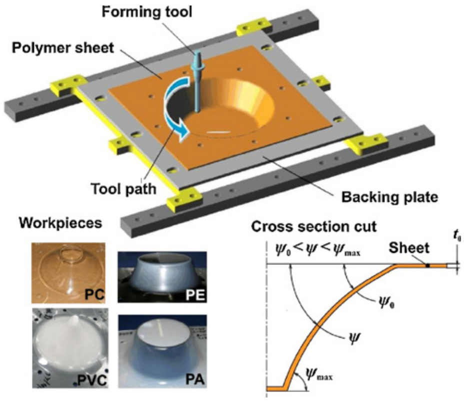

Fig. 1. Experimental setup and conical polymer parts.

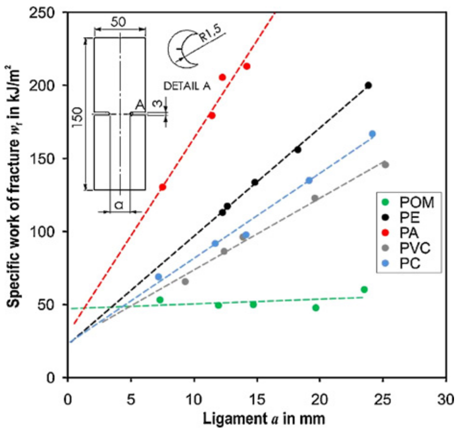

Fig. 2. Specific work of fracture w_f for DEN specimens.

Instead, fracture forming limit diagrams (FFLDs) were employed. Local necking and ductile fracture are competitive modes of failure in metallic materials [6] but in the case of PVC necking seems to be suppressed. The technique utilized for obtaining the experimental fracture forming limit (FFL) of PVC required measuring thickness at fracture in order to obtain the 'gauge length' strains ($\varepsilon_1, \varepsilon_2$). The FFL plotted in Fig. 3 can be approximated by a straight line with the expression $\varepsilon_1 + 0.28\varepsilon_2 = 0.74$. All measured material parameters are summarized in Table 1.

3. Experiments

In the experiments, commercial polymer sheets with a uniform thickness of $t_0 = 2$ and 3 mm were analyzed.

The experimental study was performed on a Deckel Maho CNC machining center equipped with a simple tool set-up comprising the following components: (i) the blank holder with a backing plate and (ii) the single-point forming tool (Fig. 1). The polymer sheet, which was fixed by the blank holder, was progressively formed by the forming tool. The tool path was generated with the CAM module of the commercial software CATIA V5. No correction methods were included in the tool path in order to observe the full deviation of the part geometry, mainly influenced by springback.

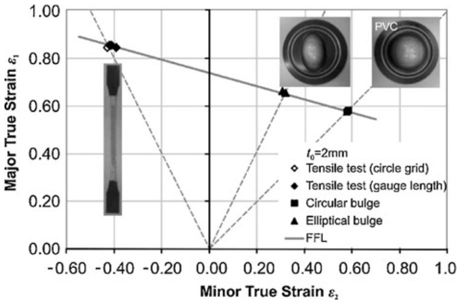

Fig. 3. Fracture forming limit diagram of PVC.

To investigate the formability in the incremental cold forming process, a conical geometry was chosen. It was characterized by an initial drawing angle Ψ_0, followed by a continuously increasing drawing angle Ψ (Fig. 1). During the forming process the material failed due to thinning.

Ham and Jeswiet [7] presented the identification of the main influencing parameters on the formability in SPIF for metals by means of DoE. They identified the material type, material thickness, the tool size, the shape of the part, and the incremental step size as main parameters. Following their approach, (i) the polymer material, (ii) the thickness of the sheet t_0, and (iii) the tool radius r_{tool}, and the initial drawing angle Ψ_0 were identified as significant process parameters for SPIF of polymers. These parameters were varied in a full factorial design at two different stages (Table 2). The tool path strategy, the vertical step size Δz, and the feed rate f remained fixed.

The target value of the DoE is the maximum drawing angle Ψ_{max}, which is directly related to the depth h of the part. After measuring the depth of the tool position at material failure, the angle ψ can be calculated by the sine law.

To keep the process temperatures on a low constant level, a soap-based emulsion was applied between the forming tool and the polymer sheet.

The geometrical shape of the manufactured parts was measured with a 3D digitalizer of GOM. The digitalized shape was re-imported into a CAD system and compared with the original CAD model to analyze the deviation.

4. Results and discussion

4.1. Modes of failure

The experiments showed the following failure modes:

(i) *Mode 1:* crack opening along the circumferential direction at the transition zone between the inclined wall and the corner radius of the parts (Fig. 4a).
(ii) *Mode 2:* development of wrinkles along the inclined wall of the parts (Fig. 4b).
(iii) *Mode 3:* crack opening along the bisector direction in the inclined wall of the parts (Fig. 4c).

The morphology of the cracks in failure mode 1 and its propagation paths along the circumferential direction are similar to those usually found in the SPIF of metals. The morphology of the wrinkles in failure mode 2 is an indication of twisting as a result of the circular tool path. The morphology of the cracks in failure mode 3 indicates shearing. It could be observed that this failure mode is related with the initial surface integrity of the polymer sheets.

Table 1
Measured properties of polymers.

Polymer	Structure	Density (kg/m^3)	Elastic modulus (MPa)	Yield stress (MPa)	Fracture toughness (kJ/m^2)
POM	H-C	1404	2894	67.6	Brittle
PE (HD)	M-C	966	961	25.3	22.2
PA	M-C	1129	2028	52.9	29.6
PVC	L-C	1469	2835	52.4	24.1
PC	A	1187	2330	63.6	22.7

Table 2
Process parameters.

Initial drawing angle, Ψ_0	Tool radius, r_{tool}	Initial thickness, t_0	Tool path	Step size, Δz	Feed rate, f
Variable			Fixed		
40°	5 mm	2 mm	Unidirectional	0.5 mm	1500 mm/min
60°	7.5 mm	3 mm			

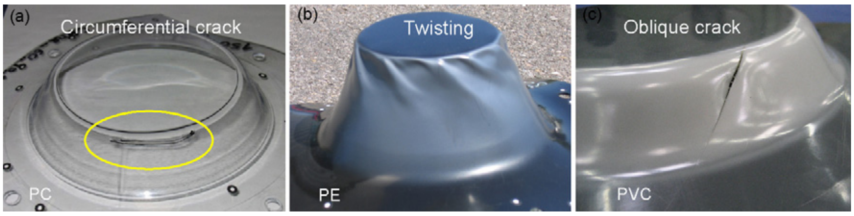

Fig. 4. Failure modes that are experimentally observed in the SPIF of polymers.

4.2. Strains at failure

The experimental technique for measuring the principal strains ($\varepsilon_1, \varepsilon_2$) in the SPIF parts involved the utilization of an adhesive grid with 2 mm initial diameter circles (Fig. 5). The solid markers refer to experimental strains at failure and were obtained from grid elements placed just outside the crack since they represent the condition of the thinned sheet at the onset of fracture.

The results confirm that SPIF of a truncated PVC conical shape is performed under plane strain conditions and also show that the formability in the SPIF of PVC is limited by fracture without significant previous necking.

4.3. Influences on the formability

Fig. 6 shows the results of the designed SPIF experiments. For the investigated materials, an increase of r_{tool} reduces the maximum drawing angle Ψ_{max} and increases the initial drawing angle Ψ_0.

The increase of the initial sheet thickness t_0 has a positive influence on the formability. In contrast to metals, the formability of polymers is strongly influenced by the value of the initial drawing angle Ψ_0.

The average maximum drawing angle Ψ_{max} exhibits a value of about 75.4°. A comparison of these results with those reported in [1] for different types of metallic materials leads to the conclusion that the formability of polymers is generally higher than that of metals. While PA and PVC show a formability near the average, the maximum drawing angle for PE reaches a high value of $\Psi_{max} = 81°$. PC shows a slightly lower maximum drawing angle than the average and POM failed very early in the forming process and is not considered in the figures.

4.4. Accuracy of the shaped parts

The evolution of the normalized springback with the initial drawing angle Ψ_0 for polymer sheet blanks with 2 and 3 mm thickness is shown in Fig. 7. The normalized springback is calculated as the ratio of the drawing angle deviation between the specified (CAD) and the actual drawing angles to the CAD drawing angle. The original CAD geometry was utilized for generating the tool path.

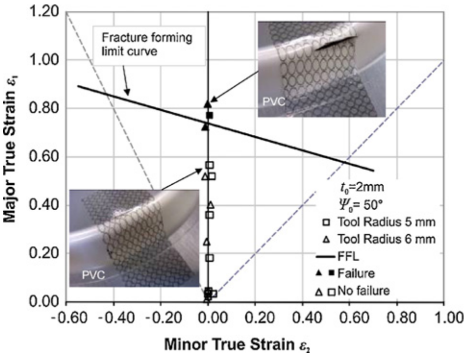

Fig. 5. Experimental strains of a PVC part.

The results indicate that springback rises with an increasing initial drawing angle Ψ_0 and falls with an increasing thickness of the sheet blanks. This means that the achievable accuracy of a SPIF part made of a polymer sheet blank with 3 mm initial thickness is higher than that of a sheet blank of the same material with 2 mm initial thickness. The experimental data also confirm that PVC SPIF parts show the least geometrical deviations compared to the original CAD geometry, PC the second least, and PA and PE parts present the largest deviations.

4.5. Variation of the color through cold forming

Tensile tests as well as SPIF experiments show that particularly the color of PVC and PE changes during forming (Fig. 8). The variation of the color is expressed by the ratio of the RGB values before and after forming.

The dark grey color of PVC turns into a light grey after forming. The initially black PE becomes grey in the formed zone. PA also changes its appearance by becoming more transparent. POM and PC look the same after forming. Franzen et al. [4] related the stress whitening effect of PVC to the density of the material, which is significantly decreased in the formed zone. To determine the change in the color of the material, snapshots of unformed and formed zones of the specimens are taken under identical lighting conditions. A comparison of the RGB values of the photographs provides information on the color change.

4.6. Material evaluation

In order to simplify the choice of polymers for SPIF applications, a material selection criterion based on ductility, springback and

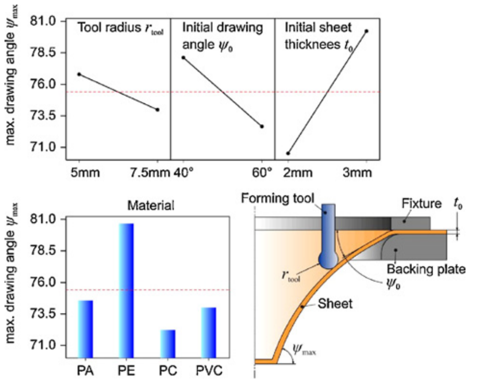

Fig. 6. Main effects on the formability.

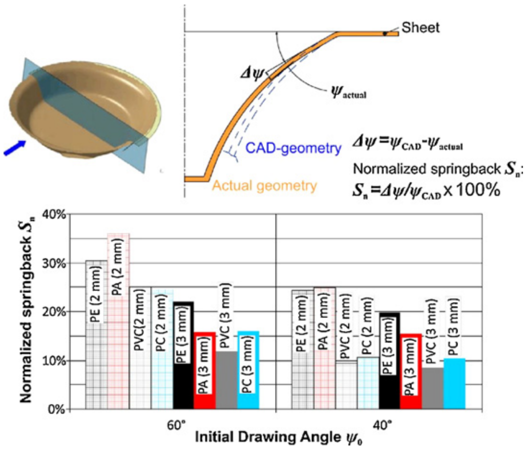

Fig. 7. Normalized springback.

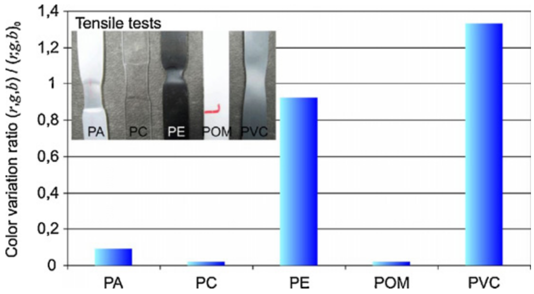

Fig. 8. Change in color after forming.

color variation features as well as the cost of raw materials is introduced as a spidergraph (Fig. 9).

The material with the best properties is defined as the benchmark and set to 100%.

The ductility factor *DF* of a material is characterized by the square of the ratio of fracture toughness *R* to yield stress σ_Y

$$DF = \left(\frac{R}{\sigma_Y}\right)^2 \tag{2}$$

DF is derived from fracture mechanics. The greater the ductility factor, the higher is the material resistance to crack growth. As a consequence, formability should increase with increasing *DF*. PE and PA reach the highest values (Fig. 9). The results presented in Fig. 5 show, that PE and PA show the best formability in the incremental cold forming process, which justifies the application of *DF*.

The springback factor *SF* of a material part is characterized by the ratio between the yield stress σ_Y and the product of thickness *t* and elasticity modulus *E*

$$SF = \frac{\sigma_Y}{tE} \tag{3}$$

The *SF* is inherent to the theory of sheet forming. The larger the *SF*, the larger the elastic recovery upon unloading and the poorer the accuracy of the SPIF parts is likely to be. In Fig. 9, PVC shows the highest values, followed by POM. Hence, PVC is set as 100% and provides the lowest springback and, therefore, the best part accuracy. This is confirmed in Fig. 7. PA provides a high normalized springback, which results in a low part accuracy and a low springback factor *SF*.

The aesthetic factor *AF* is defined as the normalized variation of the three additive primary colors of the original RGB triplet of the polymer sheet

$$AF = \frac{|(\Delta r, \Delta g, \Delta b)|}{|(r, g, b)_0|} \tag{4}$$

The results in Fig. 9 are related to the amount of variation in color of the formed parts that is induced during the SPIF of polymers. POM and PC show only a slight change in color and, hence, reach the highest values *AF*.

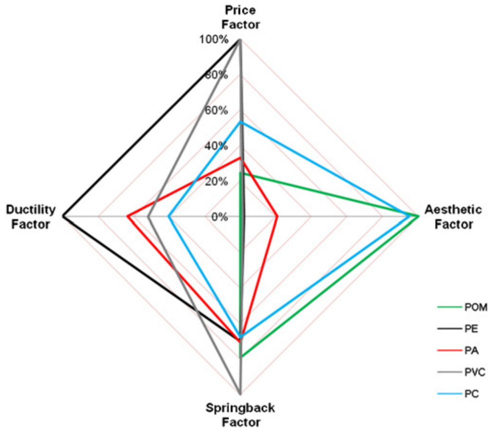

Fig. 9. Material evaluation chart.

The cost factor *CF* is defined as the ratio between the cost of the cheapest potential material C_c available for a specific SPIF application and that of the material being evaluated *C*

$$CF = \frac{C_c}{C} \tag{5}$$

The cheapest materials with the highest *CF* are PE and PVC.

5. Conclusion

It has been shown that a high formability can be obtained in incremental cold forming of thermoplastic materials. The achieved forming limits in SPIF are in accordance with the fracture forming limit curves introduced and measured during the material characterization. The suitability of materials to be processed by SPIF was evaluated, taking into account ductility, springback, and aesthetic as well as cost aspects. PE and PA showed a very high ductility and are suitable for parts with large wall angles. PVC has a low springback and should be used if a high part accuracy is demanded. PC showed only a slight change in color during the incremental cold forming process and is recommended in case of high surface quality demands. POM presented the poorest performance of all investigated polymers because it has a very limited ductility. Its utilization should not be considered for producing SPIF parts. PA showed the highest springback, which decreases part accuracy unless a modified tool path is used.

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