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Preliminary investigations on Double Sided Incremental Forming of thermoplastics

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Abstract

Single Point Incremental Forming (SPIF) of polymers has gained significant attention due to the high material formability, absence of external heating of the polymer, and the use of part-shape-independent tooling. Despite the advantages of Double Sided Incremental Forming (DSIF) of metals, polymer DSIF has not yet been explored. This study examines DSIF of a PVC polymer. Forming forces, formability and void structure of the formed polymer in SPIF and DSIF are compared. Significant advantages of polymer DSIF over SPIF are observed including greater formability, reduced void growth in the material and reduced sheet bending outside the desired forming region.

Keywords: Double Sided Incremental Forming; Polymers; Formability; Forces; Void area fraction

1. Introduction

Single Point Incremental Forming (SPIF) locally deforms a fully peripherally clamped sheet using a small hemispherical ended tool moving along a pre-defined 3D toolpath [1–4]. Double Sided Incremental Forming (DSIF) uses one such tool on either side of the sheet, such that one tool forms the sheet and the other tool supports or squeezes the sheet locally. Past work on DSIF of metals [5–8] has shown significant advantages over SPIF, including higher formability and improved geometric accuracy. SPIF of commodity and engineering thermoplastics including PVC, PLA, Polyamide, PET, PC and POM has been demonstrated [9–15], without the need for any external heating of the polymer. Currently, thermoplastic surfaces for prototyping and replacement in automobile interiors, low volume fabrication in aircraft interiors [16] and packaging are typically fabricated via injection molding or hot forming. The reduced cost of thermal energy and tooling in polymer incremental forming can reduce the manufacturing costs in these applications. Furthermore, thermoplastics are more amenable to meeting fire safety standards in the automotive and aerospace industries than thermosets [17]. Despite the above advantages of DSIF, polymer DSIF has not yet been explored. This paper reports preliminary experimental work performed to explore the feasibility of polymer DSIF. SPIF, Conventional DSIF (CDSIF) and Accumulative DSIF (ADSIF, [8]) of commercially obtained PVC are compared in terms of key process and material indexes including forming forces, formability and void content of the formed polymer. These indexes are characterized in terms of the incremental depth (Δz), i.e., the step down in the part depth direction in each consecutive pass of the tool [1], the squeeze factor (s), i.e., the amount by which the two tools squeeze the sheet [18], and the part

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shape. The feasibility and advantages of polymer DSIF over SPIF are demonstrated and future research directions for polymer DSIF are discussed.

2. Experiments

A DSIF machine [5,6,8] with a forming area of $250 \times 250\ mm^2$, and two tool-mounted load cells for measuring forming forces, was used to form 1.6 mm thick PVC sheets with 10 mm diameter tools. A PTFE based grease was used as the lubricant at the tool-sheet interface with a tool feed rate of 10 mm/s. A 60° wall angle cone and a funnel shape, with radius of curvature R_f of 80 mm and 150 mm and continuously changing wall angle from 30° to 90° (Fig. 1a), were formed with CDSIF using $\Delta z = 1.2$ mm and 1.8 mm. Squeeze factors s of 0.8 and 1.0 were investigated. Note that when $s = 1.0$ the bottom tool is just touching the sheet and when $s < 1.0$, the tools are actively squeezing the sheet in the local deformation region between the two tools [5]. SPIF and ADSIF of the cone shape were also performed using $\Delta z = 1.8$ mm. In CDSIF and ADSIF, the bottom tool was positioned based on the sine law [5]. All experiments were performed using a spiral toolpath (Fig. 1b, [1]).

3. Results

Fig. 2a–e shows parts formed with SPIF, CDSIF and ADSIF. The fracture depth and wall angle are commonly used to describe the formability in incremental forming. At the same Δz (Table 1) the formed depth of the cone is greater with CDSIF (Fig. 2b) and ADSIF (Fig. 2c) than with SPIF (Fig. 2a), indicating greater formability with DSIF. In fact, no sheet failure is observed with ADSIF. Furthermore, in CDSIF a reduction in s (i.e., greater squeezing of the sheet) and an increase in Δz increases the formability (Table 1). Greater formability with greater Δz has also been observed in polymer SPIF [15], which is the opposite trend to that seen in metal SPIF. The formability also seems to depend on the overall part shape, as in polymer SPIF [15], since the funnel with $R_f = 150$ mm (Fig. 2e) is deformed to a greater wall angle than the funnel with $R_f = 80$ mm (Fig. 2d).

A closer observation of the side of the sheet in contact with the bottom tool (Fig. 2b) and of the forming forces (Fig. 3a) in CDSIF, shows a gradual loss of contact between the sheet and the bottom tool. This phenomenon is also seen in metal CDSIF [18,19]. A concurrent change in the color of the sheet was observed, from grey when tool-sheet contact was retained to whitish-grey when tool-sheet contact was lost. This color change indicates the occurrence of crazing [9] after tool-sheet contact is lost in CDSIF, which typically leads to growth of larger voids and fracture. In ADSIF there is no loss of contact between the bottom tool and the sheet (Figs. 2c and 3b) and no change in color of the polymer. This absence of crazing is probably the reason behind higher formability in ADSIF than in CDSIF. Fig. 4a–e shows representative SEM images of the outer surface of the formed parts, along with binary images (inset) obtained after image processing with ImageJ software. Multiple such images were analyzed to calculate the surface void area fraction in the formed material (Fig. 4f). The void area fraction is much higher for SPIF than for CDSIF in the region of the part where tool-sheet contact is retained. When contact is lost in CDSIF, the void area fraction rises to levels similar to those in SPIF. Since tool contact is not lost in ADSIF the void area fraction stays low. This observation further supports the hypothesis that retention of tool-sheet contact in ADSIF reduces crazing and resultant void growth in the polymer, resulting in greater formability with ADSIF as compared to CDSIF and SPIF. For the cone shape, the geometric definition of the interface between the wall of the formed part and the ideally flat part of the sheet was observed to be significantly improved with CDSIF and ADSIF than with SPIF (Fig. 2a–c). This indicates a reduction in the unwanted bending of the sheet outside the desired deformation zone with DSIF. A similar degree of geometric definition can also be seen in CDSIF of the funnel shape (Fig. 2d and e).

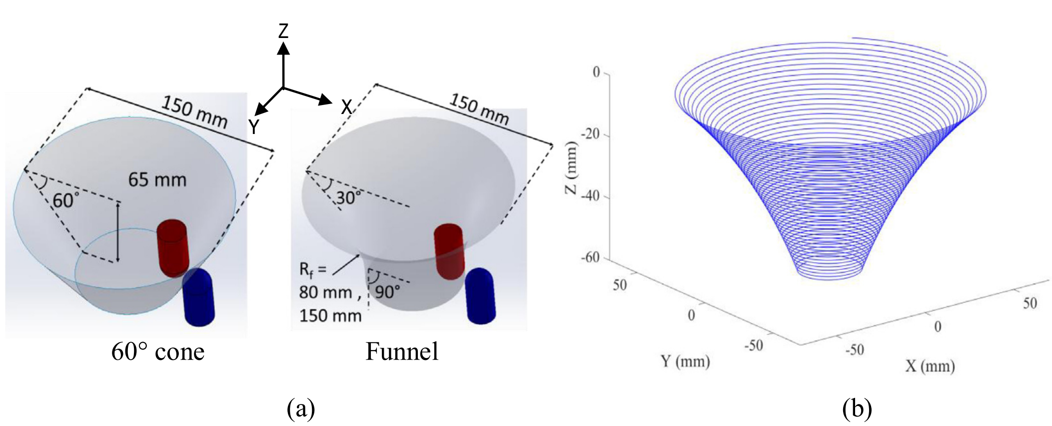

Fig. 1. (a) Schematic of formed cone and funnel parts. (b) Representative example of spiral toolpath used, shown here for a funnel shape.