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Effects of incremental depth and tool rotation on failure modes and microstructural properties in Single Point Incremental Forming of polymers

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ABSTRACT

Single Point Incremental Forming (SPIF) is a sheet forming process characterized by advantages that include low-cost and part-shape-independent tooling, higher formability and greater process flexibility as compared to conventional sheet forming. While recent work has demonstrated the possibility of SPIF of polymers the effects of incremental depth and tool rotation speed, key process parameters in SPIF, have rarely been examined. This work experimentally examines how incremental depth and tool rotation speed affect the failure mode during forming, forming forces as well as the void structure and crystallinity of the formed material in polymer SPIF. The dependence of both tearing and wrinkling on the incremental depth and tool rotation speed is uncovered. It is shown that contrary to SPIF of metals, greater incremental depths result in increased formability in polymer SPIF, but this advantage is limited by the occurrence of sheet wrinkling at excessively high incremental depths. Further, the occurrence of sheet wrinkling depends not just on the incremental depth but also on the part shape being formed. Microstructural examination of the formed material shows that greater incremental depth results in greater void densities and that the material formed with SPIF has greater crystallinity than the unformed material. Additionally, it is shown that higher tool rotation speed can cause earlier onset of wrinkling. The implications of these observations on SPIF of polymers are discussed.

1. Introduction

Single Point Incremental Forming (SPIF) is a process in which a completely peripherally clamped sheet of material is locally deformed by a small hemispherical ended tool moving along a predefined toolpath. These local deformations accumulate to give the sheet its final desired shape. A significant amount of research has been performed on SPIF of metals in terms of deformation and fracture mechanics, forming forces, toolpath planning, geometric accuracy and surface finish in the process. Recent work on SPIF of polymers has also uncovered the possibility of expanding the materials capability window of SPIF beyond metals, by demonstrating SPIF of thermoplastic polymers at room temperature. This creates the possibility of saving on both tooling costs as well as on the thermal energy costs, which are inherent in injection molding or thermoforming processes that are typically used to fabricate freeform thermoplastic surfaces. Further, cold-state SPIF results in reduced heating of the sheet which is highly desirable for temperature sensitive biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs). This lowered heating can alleviate thermal degradation and retain the virgin material properties that would have been lost in conventional fabrication processes. Past work on polymer SPIF has performed both experimental and computational investigations. Franzen et al. (2009) experimentally examined the feasibility of forming polyvinyl chloride (PVC) sheets into axi-symmetric shapes using SPIF. The following three modes of sheet failure were observed:

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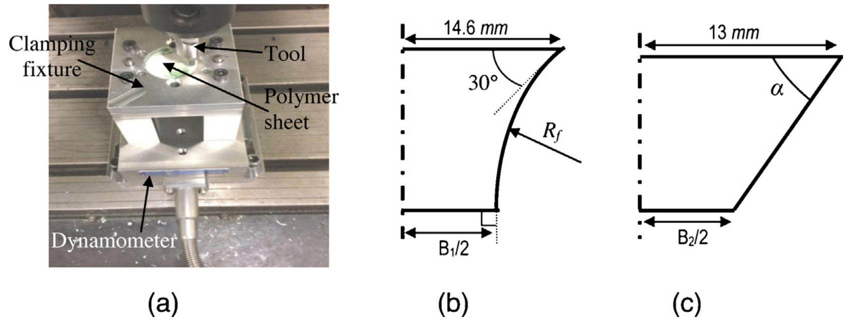

Fig. 1. (a) SPIF setup, (b) profile of formed funnel shape, and (c) profile of formed cone shape.

Mode 1: Sheet fracture by ductile tearing along the circumferential direction, at the transition between the wall and the corner radius of formed parts.
Mode 2: Wrinkling of the sheet along the wall of the part.
Mode 3: Tearing of the sheet in the radial direction, along the wall of the part.

The authors noted that only Mode 1 failure is typically seen in SPIF of metals and that Mode 3 failure is probably due to the occurrence of defects in the as-received sheet. The authors also showed stress whitening in the formed PVC material, and noted that this was probably due to deformation induced crazing in PVC. Martins et al. (2009) further extended the above work to show that a reduction in tool radius and an increase in the sheet thickness result in increased formability in polymer SPIF, much like in metals SPIF. Franzen et al. (2008) performed SPIF of five different polymers with varying degrees of crystallinity. It was shown that the reduction in density of the formed PVC material was larger than that of materials like polycarbonate and polyamide. The authors also experimentally demonstrated that the change in formed material density depends on the wall angle of the part being formed, and therefore on the strain induced in the material during SPIF. Furthermore, the dependence of springback on the sheet material properties was qualitatively examined in terms of the ratio of the yield stress of the material to the product between the thickness and elasticity modulus of the sheet material. Silva et al. (2010) focused on computationally examining the deformation mechanics in polymer SPIF by extending the membrane-based analysis developed by Martins et al. (2008) via a pressure modified Tresca yield criterion. This single-step analysis models only Mode 1 failure by tearing and considers the influence of part shape, tool diameter, sheet thickness and mechanical properties of the polymer sheet on tearing in polymer SPIF. The authors successfully predicted experimental observations that reducing the tool radius can increase the formability of the material, more so for thicker sheets than for thinner sheets. However, due to the single-step nature of analysis this technique did not account for the effects of incremental depth (Δz) on Mode 1 and Mode 2 failure. The above literature review shows that the effects of incremental depth Δz and tool rotation ω on polymer SPIF have rarely been explored till date. The basis for expecting an effect of Δz, especially on the sheet failure modes, arises from the fundamental nature of deformation in SPIF in which a change in Δz can create a change in the stress history imposed on the sheet material. Past work on metal SPIF Xu et al. (2013) has shown that tool rotation, and the resulting frictionally generated heat, can significantly increase formability and reduce the forming forces. A similar effect can be expected in polymer SPIF as thermoplastics exhibit softening and increase in ductility when heated.

This paper characterizes the effects of Δz and ω on failure, forming forces, as well as void content and crystallinity of the formed material in polymer SPIF. The experiments performed are described in Section 2. Section 3 describes the observed effects of Δz and ω on failure modes. We go beyond just Mode 1 failure and uncover a distinct transition between Mode 1 and Mode 2 failure that is dependent on the above process parameters as well as on the part shape being formed. Furthermore, the effects of Δz and ω on void density and crystallinity of the formed material are obtained via Scanning Electron Microscopy and Differential Scanning Calorimetry. Section 4 discusses the implications of these observations in terms of failure modes during polymer SPIF, process throughput and formed material properties, along with a discussion on possible directions for future work.

2. Experimentation

An SPIF setup with a circular forming area of 40 mm diameter was assembled on a HAAS CNC machine platform (Fig. 1a). This setup consisted of the following components: (i) the clamped polymer sheet, (ii) the blankholder mounted onto a Kistler 9257B plate type dynamometer, and (iii) the forming tool mounted on the CNC spindle. The dynamometer was mounted onto the bed of the CNC and was used to monitor the forming forces during SPIF. No backing die was used and a PTFE-based grease was used as the lubricant at the tool sheet interface during all experiments.

To examine the effect of Δz and ω on failure modes two kinds of part shapes were formed namely, funnel shapes (Fig. 1b) with continuously varying wall angle from 30° to 90° and a variable radius of curvature R_f and cone shapes (Fig. 1c) with variable wall angle α. For the funnel shape the base diameter B_1 varied from a minimum of 8.1–16 mm whereas for the cone shape the base diameter varied from 8.6–17 mm. Since a tool of diameter 5 mm was used in all the SPIF experiments shown in this paper there was no interference of the tool with the already formed region of the sheet during forming.

The funnel shape has been frequently used to examine formability in metal SPIF (Hussain and Gao, 2007) since its geometry

Table 1
Summary of experimental parameters used.

Material	Incremental depth Δz (mm)	Tool rotation speed ω (rpm)	R_f (mm)	α (degrees)
PLA	0.2, 0.4, 0.6, 0.8, 1.0	0, 1250, 5000, 7000	10, 12, 14, 16	55, 65, 75
PVC	0.2, 0.6, 1.0, 1.4, 1.8	0, 1250, 5000, 7000		