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Effective forming strategy for double-sided incremental forming considering in-plane curvature and tool direction

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ABSTRACT

The success of a toolpath in double-sided incremental forming (DSIF) is strongly related to the specified tool gap. It is hypothesized in this work that maintained contact between tools and the sheet can improve the distribution of sheet thickness and hence, improve material formability and prevent premature fracture. Simulation and experimental studies reveal that thickness prediction models solely dependent on the local wall angle are inadequate for general part geometries. A 'Shamrock' geometry is proposed leading to the development of a novel improved thickness correction model that incorporates wall angle, in-plane curvature, and tool direction.

1. Introduction

Double-sided incremental forming (DSIF) is a flexible, die-less manufacturing process that utilizes generic tooling to locally deform sheet metal into freeform geometries. By using two tools, one above and one below the clamped sheet, highly-customized parts can be formed using toolpaths generated directly from a CAD part (Fig. 1). Although single-point incremental forming (SPIF) exhibits excellent material formability [1] and the potential for closed-loop accuracy feedback [2], DSIF provides increased control during material deformation [3] resulting in enhanced geometric accuracy [4] and also further increasing formability [5].

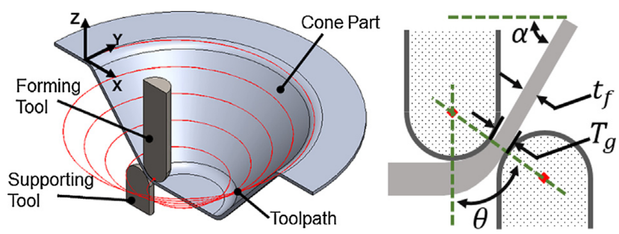

Fig. 1. Left: Cross-section of DSIF; right: tool position parameters.

The relative tool positioning of the two tools is given by Fig. 1, where α is the wall angle, θ is the angle between the tools with respect to the Z-axis, t_f is the deformed thickness, and T_g is the tool gap. While closed-loop control of tool positioning based on forming forces in situ of DSIF has been investigated by Meier et al. [6], the use of displacement control is still an attractive option for general parts in industry because of the simplicity in machine and controller design, as well as fast response time and robustness to variations in material properties. However, estimates of sheet thinning and machine compliance must be calculated prior to physical forming in order to prevent the supporting tool from losing contact with, or over-squeezing, the sheet metal.

The study presented in this paper was motivated by an observation found in experiments regarding the importance of maintaining tool contact. Fig. 2 illustrates a DSIF-formed circular funnel. Interestingly, fracture occurred within the section of sheet which lost contact with the supporting tool, while the opposing region maintained contact with both tools and evidently did not experience fracture. Similar discoveries were observed related to the location of fracture initiation for other parts formed by DSIF, including a truncated pyramid. In the event that the supporting tool loses contact with the sheet, the DSIF process inherently degenerates into SPIF, thus eliminating the through-the-thickness pressure provided by the supporting tool which helps to delay fracture [7]. To maximize formability in DSIF, our hypothesis is that one must maintain both tool contacts during the entire DSIF process.

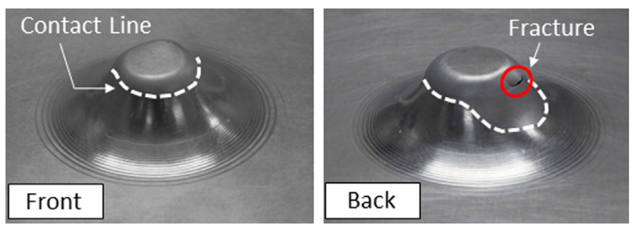

Fig. 2. Fracture initiated where contact was lost.

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Factors that can contribute to the loss of tool contact with the sheet typically involve either inaccurate thickness prediction, tool misalignment, or unaccounted for machine compliance. In Fig. 2, the part is axisymmetric and lost contact likely due to a tool misalignment. However, inaccurate thickness prediction is the most common culprit. In incremental sheet forming, the part's thickness is often predicted by the Sine law, $t_f = t_0 \sin(90^\circ - \alpha)$ where t_0 is the initial thickness. However, the Sine law is dependent on just the wall angle and thus is not well-suited for general features.

Our investigation of the relation between wall angle and loss of contact initiated with the truncated pyramid geometry (Fig. 3). This part geometry contains four sides with different, constant wall angles, though, contact was still lost in some regions. In particular, it was observed that contact was lost at the corners between the four sides implying that part curvature likely plays a role in the loss of contact between the sheet and the tools.

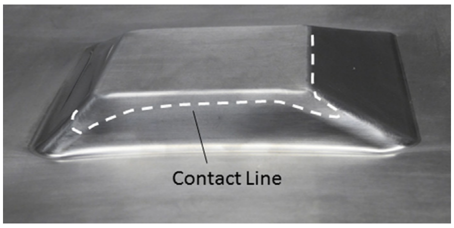

Fig. 3. Asymmetric contact loss on truncated pyramid part.

2. Analysis of the in-plane curvature effect on thickness

In this work, we will prove the need to use in-plane curvature when compensating for machine compliance and sheet thinning for DSIF toolpaths. Additionally, a novel correction model is presented and demonstrated on a part geometry, named the 'Shamrock' part, specifically designed to decouple wall angle from in-plane curvature as shown in Fig. 4. The Shamrock part has a combination of both concave and convex in-plane curvatures, and its wall angle is kept constant around the contour regardless of the in-plane curvature. The existence of four repeating regions is to examine tool alignment or material anisotropy.

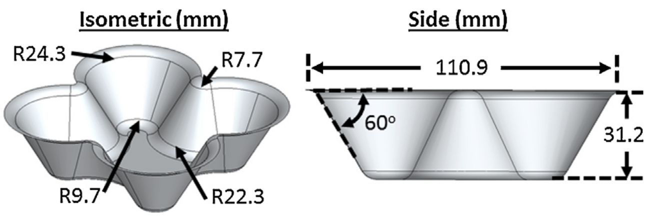

Fig. 4. 'Shamrock' part with constant wall angle.

2.1. Curvature definition and its relation with tool movement

Based on the local in-plane contour of the geometry, different regions of the part can be defined as either 'inward' or 'outward' and either 'departing' or 'approaching'. To illustrate these concepts, the definitions are marked in Fig. 5 along with an in-plane cross-section contour of the Shamrock design. Note that the motion direction of both tools is illustrated as well, in this case, they are moving in the counter-clockwise direction.

If the center of curvature lies within the interior of the contour, then the region is termed 'inward'. Contrarily, if the center of curvature lies outside the contour, then the local point is termed 'outward'. The 'approaching' and 'departing' regions are defined using β, i.e., the angle between the contour's tangent vector and the vector connecting the centroid to the local point. If the angle $\beta > 90^\circ$, then the local region is defined as a 'departing,' whereas if $\beta < 90^\circ$, it is defined as an 'approaching' region. Notice that the length of the vector between the local point and the centroid increases within the 'departing' region, and vice versa for the 'approaching' region.

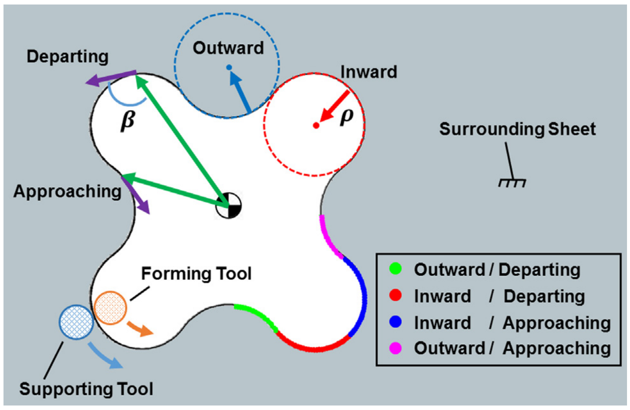

Fig. 5. One corner, or leaf, of the Shamrock part has been separated into four categories based on curvature and tool motion.

According to the above definitions, one leaf or corner of the Shamrock part can be divided into four different regions as shown in Fig. 5: 'outward/departing' (green), 'inward/departing' (red), 'inward/approaching' (blue) and 'outward/approaching' (magenta).

Fig. 6 shows the locations of lost-contact areas in two identical parts formed using the same toolpath parameters except for the direction of tool motion. Details of the experimental parameters and conditions are given in Section 3. Two observations can be immediately made: (1) the loss of contact locations are consistent for a given part in that the region favors a particular side of the leaf and (2) there appears to be a link between tool motion and loss of contact. The first observation eliminates tool alignment, tool asymmetry, or machine error as the causes of contact loss in our experiments. Related to the second observation, we can observe that the 'inward/approaching' region (blue region) in both clockwise and counter-clockwise cases lost contact, while the contact is usually maintained well in the 'outward' regions (green and magenta).

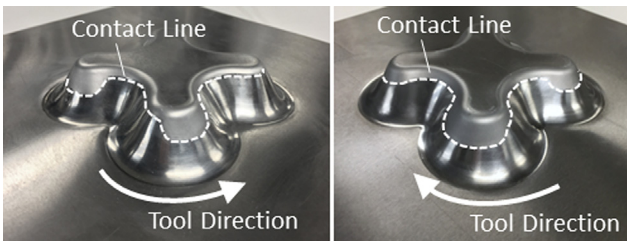

Fig. 6. Asymmetric loss of tool contact around rounded corners.

2.2. Investigation using finite element analysis

Simulation studies using LS-DYNA's finite element analysis (FEA) software package were performed to verify and explain the loss of contact observations found in the aforementioned Shamrock experiments. Aluminum 5754-O (1 mm thick) was solely considered for all experiments and simulations to be discussed. As described by Moser et al. [8], an isotropic elasto-plastic model (J_2-plasticity) can be utilized for this material and still capture the prevalent mechanics that occur during the DSIF process. The sheet blank (150 mm × 150 mm) was modeled using a uniform grid of 0.5 mm shell elements, namely LS-DYNA's shell element ID 26. This particular shell element is fully integrated and has a thickness stretch in order to adequately capture through-the-thickness effects. The tools were modeled with rigid elements and were sped up to 750 mm/s. Explicit time integration was chosen with mass scaling used to raise the stable time step to $1(10^{-5})$ s. Using 16 CPUs, approximately 1 week was required to complete the simulation.