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Accumulative-DSIF strategy for enhancing process capabilities in incremental forming

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ABSTRACT

This work proposes a novel *Accumulative Double Sided Incremental Forming* (ADSIF) strategy in which the forming begins at the location of the deepest feature and gradually shapes up the features by taking advantage of rigid-body motions. Compared to the conventional toolpath used in DSIF and SPIF, this strategy can dramatically improve geometric accuracy, increase formability, form components with desired thickness and create complex components. Furthermore, an examination of the forming forces shows that the dominant forces using this strategy are in the plane of the sheet resulting in a significant improvement in geometric accuracy.

1. Introduction

Incremental forming (IF) is a flexible sheet metal forming technique that uses simple generic tooling to locally deform sheet metal along a predefined toolpath, imparting the sheet a desired shape. Single Point Incremental Forming (SPIF) uses one tool on one side of the sheet to cause the deformation. SPIF is plagued by an inherent geometric inaccuracy due to non-local springback in the single point setup. Allwood et al. [1] attempted to improve the geometric accuracy by using partially cut out blanks along the periphery of the forming area. While the obtained geometric accuracy was better than that in regular SPIF, they commented that this technique was not useful in improving geometric accuracy in IF, especially in comparison to the significantly better geometric accuracy provided by a partial support in spite of the resultant loss in process flexibility. Allwood et al. [2] also used closed-loop feedback control to improve the geometric accuracy in SPIF by forming the component in a second iteration. Although the result obtained from the second iteration was better than the initial one, they mentioned that this strategy would be difficult to be implemented for freeform objects.

Variations of IF have been proposed to preserve its inherent process flexibility and to improve geometric accuracy, mainly die-based IF which uses a die below the sheet (DBIF in Fig. 1a) and double-sided IF which uses one tool on either side of the sheet (DSIF in Fig. 1b). In DBIF, for example, Tekkaya et al. [3] used generic sectional shapes to act as supports for the forming tool assisted with an analytical tool that calculates thinning to achieve a better geometric accuracy in IF. However, the strategy is limited to forming components on one side of the sheet only and requires process planning that is specific to the part geometry being formed.

An interesting alternative is the DSIF setup as demonstrated by Meier et al. [4] who used two tools on either side of the sheet, each tool mounted on a robot. Malhotra et al. [5] showed that using two identical tools on either side of the sheet with the gap between tools smaller than the sheet thickness, a so-called "squeezing toolpath", can improve the geometric accuracy, particularly for forming tight radii or small fillets. However, they also pointed out that an accurate thickness prediction is critical in this toolpath, otherwise, due to loss of contact between the bottom tool and the sheet, DSIF will degenerate to SPIF. To maintain contacts of both tools with the sheet, Meier et al. [6] used a forming tool which was displacement controlled whereas the supporting tool used a combination of displacement and force control. They demonstrated that this strategy could ensure contact between the supporting tool and the sheet at all times, leading to greater formability. However, a drawback of this strategy is that the amount of force to be applied and a preset angular offset for the supporting tool have to be worked out by repetitive trials every time the component shape is changed. Furthermore, depending on the global shape of the component the force required will change. Therefore, to form a freeform shape the amount of force required will vary spatially and will have to be pre-determined by experimental iterations.

In past works on DSIF [5,6], the conventional out-to-in toolpath has been employed for the forming tool. In this toolpath the forming begins from the outermost periphery of the component to be formed and travels all the way down to the actual component depth, while moving in the X–Y plane (Fig. 2a).

This work proposes a novel *Accumulative Double Sided Incremental Forming* (*ADSIF*) strategy for DSIF where both the forming tool and the supporting tool are purely displacement controlled.

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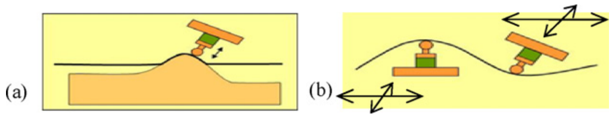

Fig. 1. Schematic of existing DSIF strategies (a) die-based IF (DBIF) and (b) Double Sided Incremental Forming (DSIF).

Contact between both tools and the sheet are maintained at all times during the forming process. Once the strategy is understood, it is surprisingly easy to generalize it for a freeform geometry since the toolpath can be decided completely a priori based on the CAD geometry.

In the following sections, the toolpath strategy for *ADSIF* will be detailed first followed by an experimental demonstration of forming components with features on both sides of the blank as well components with concavo-convex features, without flipping the sheet or changing the tooling in the forming process. The effects of *ADSIF* on geometric accuracy, formability, thickness distribution and forming forces will then be presented and analyzed.

2. Fundamentals of *ADSIF*

Malhotra et al. [5] demonstrated that the sine law provided an inaccurate prediction of the formed thickness in DSIF. Therefore, positioning the second tool based on the sine law in a conventional out-to-in toolpath leads to loss of contact and unsatisfactory geometric accuracy during DSIF. The proposed *ADSIF* strategy was originally conceived by co-authors of Ford [7] and has been enhanced here in this work and in the corresponding patent application [8]. This strategy prevents loss of contact without using any shape specific adaptive strategies, while using the simple sine law to position the bottom tool. This section explains the theory behind *ADSIF*.

For simplicity, consider the forming of a cone with the top tool as the forming tool and the bottom tool as the supporting tool. In a conventional out-to-in DSIF toolpath (Fig. 2a), forming begins at the largest diameter of the cone and ends at the smallest diameter, while the tool travels simultaneously in the *X*, *Y* and *Z* directions. If a constant incremental forming depth (Δz) is used, by the 3rd pass both tools will be at *Z* positions of $-3\Delta z$.

When using ADSIF to form the same cone (Fig. 2b), the forming process begins from the smallest diameter and ends at the largest diameter of the cone. First, the forming and supporting tools form the material to a depth equal to the specified incremental depth Δz in the 1st pass. Then, in the 2nd pass, both the forming tool and the supporting tool move outwards in the *X–Y* plane but maintain the same *Z* position. Consequently, the 2nd pass deforms the next outlying region of the material by Δz. Meanwhile, due to the rigid body movement, the region of the blank formed in the 1st pass is displaced down in the negative *Z* direction by an amount equal to Δz. Hence, the *Z* position of the component base after the 2nd pass is $-2\Delta z$. Similarly, when the 3rd pass is formed, the component base is at a *Z* position of $-3\Delta z$ while both tools are still at a *Z* position of $-\Delta z$. The shape of the component in the *X–Y* plane is controlled by the motion of the forming and supporting tools as generated from the CAD model. The local angle generated at each deformation point is controlled by the position of the supporting (bottom) tool in relation to the forming (top) tool. As shown in Fig. 3, the local wall angle θ is equal to the angle subtended to the vertical by the line segment OO' connecting the centres of the two hemispherical tools. Therefore, the position of the bottom tool is calculated according to Eq. (1).

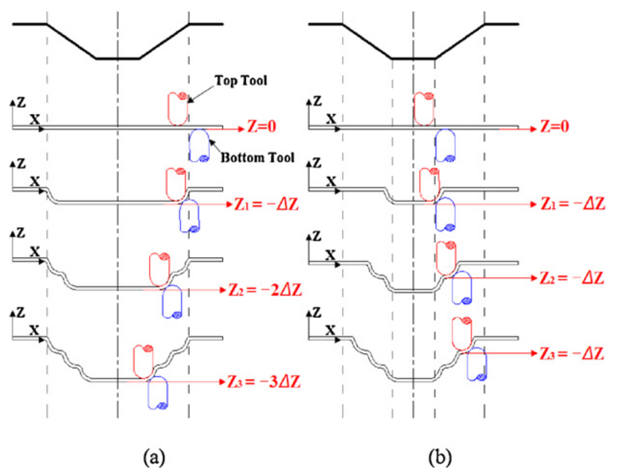

Fig. 2. Illustrations of (a) conventional DSIF toolpath strategy and (b) proposed *ADSIF* strategy.

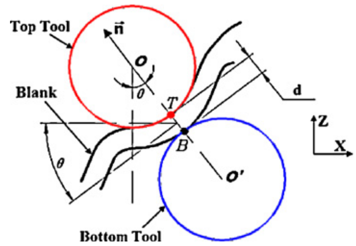

Fig. 3. Schematic showing positioning of the two tools in *ADSIF*.

$$\vec{O'} = \vec{O} - (R_1 + R_2 + d)\vec{n} \tag{1}$$

where $\vec{O'}$ is the vector coordinate of the bottom tool centre, $\vec{O}$ is vector coordinate of the top tool centre, R_1, R_2 are radii of top and bottom tools, respectively, $\vec{n}$ is the unit normal at the local contact point *T* (Fig. 3).

The distance *d* between the closest surfaces of the hemispherical tools is decided based on the sine law (Eq. (2)) and is essentially the desired thickness of the deformed wall. The constant *s* ($\leq$1.0) decides the amount of squeezing that the sheet experiences. All components shown henceforth in this work were formed with *s* = 1.0, except when explicitly stated otherwise.

$$d = (t_0 \cos\theta)s \tag{2}$$

where t_0 is the original blank thickness.

The sequential steps for generating the toolpath in *ADSIF* are illustrated in Fig. 4 and are as follows:

a. The contact points and the corresponding normal are generated on the contour at a particular *Z* depth, $Z = Z_1$ (Fig. 4a).
b. The contact point is projected onto the $Z = -\Delta z$ plane (Fig. 4b) to obtain the contact point of the top tool (i.e. point *T* in Fig. 3). The bottom tool contact point (i.e. point *B* in Fig. 3) is calculated based on Eqs. (1) and (2) (Fig. 4c).
c. The tool tip points for the forming tool (TT_{top}) and supporting tool (TT_{bottom}) are generated according to Eqs. (3) and (4).

Essentially, instead of simultaneously controlling the *X*, *Y* and *Z* locations of deformation as in a regular DSIF/SPIF toolpath, the toolpath in *ADSIF* controls the local formed angle in the *X–Y* plane and the shape formed in the *X–Y* plane. The local formed angle

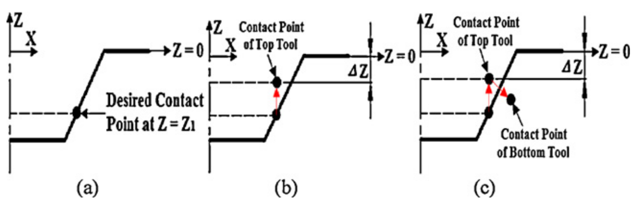

Fig. 4. (a) Desired contact point generated, (b) IO forming tool contact point generated, and (c) supporting tool contact point generated.