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A new methodology for multi-pass single point incremental forming with mixed toolpaths

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ABSTRACT

A challenge in Multi-Pass Single Point Incremental Forming (MSPIF) has been the geometry control of formed components, especially on the base of the component where multiple stepped features are formed unintentionally. This work attributes the step formation to the rigid body motion during the forming process and develops analytical formulations to predict such motion during each intermediate pass. Based on this model, a new toolpath generation strategy is proposed to achieve a smoother component base by using a combination of in-to-out and out-to-in toolpaths for each intermediate shape.

1. Introduction

Single Point Incremental Forming (SPIF) is a die-less flexible forming process that locally deforms sheet metal using a moving tool head, achieving higher forming limits than those in conventional sheet metal stamping process as reviewed in Jeswiet et al. [1]. However, conventional SPIF has limitations with respect to maximum formable wall angle, thickness distribution and geometric accuracy of the component as described in Malhotra et al. [2]. There have been attempts to increase the formability in incremental forming using multiple passes, first in Hirt et al. [3] using Two-Point Incremental Forming. In SPIF, Skjoedt et al. [4] used a five-stage strategy (Fig. 1a) to form a cylindrical cup with a wall angle of 90° using two approaches, namely, Down-Down-Down-Up (DDDU) and Down-Up-Down-Down (DUDD). Duflou et al. [5] redistributed the normally undeformed material from the horizontal region of the blank to form vertical walls without failure (Fig. 1b). Their toolpaths always moved from the periphery towards the centre of the sheet. The toolpath strategies used till date for Multi-Pass Single Point Incremental Forming (MSPIF) result in the formation of stepped features on the base of the component as shown in Fig. 1a and b. Note that the components shown were made as part of this work using the toolpath strategies in [4,5]. There have been attempts to improve the geometric accuracy achievable by Incremental Forming. Duflou et al. [6] proposed reforming the component after forming it once, based on measured geometric deviations. Verbert et al. [7] proposed processing different component features separately to generate the toolpath. Allwood et al. [8] proposed a closed-loop control strategy using spatial impulse responses to control the product accuracy in SPIF. They fitted a Weibull distribution curve to impulse responses from a set of experiments for a cone and then formed similar cones with ±0.2 *mm* accuracy.

This work investigates the mechanism by which stepped features are generated in MSPIF. Analytical formulations are developed and experimentally verified to predict this stepped feature generation. Based on this prediction capability a new generic toolpath strategy is proposed to prevent stepped feature generation in MSPIF. Furthermore, experiments are performed to show that the proposed toolpath strategy successfully achieves a smoother component base.

2. Mechanism and prediction of stepped feature generation

In this work two kinds of toolpaths are used for MSPIF. When the tool motion is from the periphery of the sheet towards the centre of the sheet, while moving in the negative Z direction, the toolpath is called out-to-in (OI) (Fig. 2a). When the tool motion is from the centre of the sheet towards the periphery, while moving in the positive Z direction, the toolpath is called in-to-out (IO) (Fig. 2b). For both OI and IO toolpaths when the $(n+1)^{th}$ intermediate shape is being formed, the region of the n^{th} shape where $r < r_{tool}$ undergoes a rigid body translation in the negative Z direction. If only OI or IO toolpaths are used to form every intermediate shape the cumulative effect of these rigid body translations is to cause stepped features on the final formed component as shown in Fig. 1b.

2.1. Modelling rigid body translation in OI toolpath

The rigid body translation for the OI toolpath is modelled by assuming that while the $(n+1)^{th}$ shape is being formed, the region of the n^{th} shape where $r < r_{tool}$ behaves like a modified cantilever beam subjected to a large elastic deformation [9]. For any contact point along the profile of the $(n+1)^{th}$ shape, the corresponding point on the n^{th} shape is obtained by projecting the contact point onto the n^{th} shape, in a direction normal to the n^{th} shape (Fig. 3). The distance Δy between the contact point on the $(n+1)^{th}$ shape and the corresponding projected point on the n^{th} shape (Fig. 3) can

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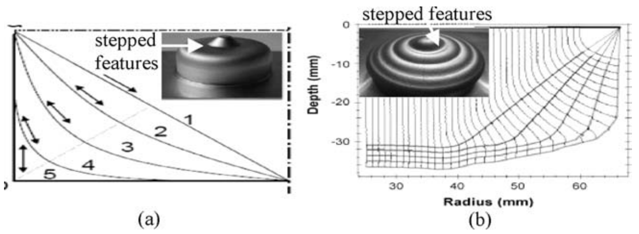

Fig. 1. Current MSPIF strategies: (a) Skjoedt et al. [4] and (b) Duflou et al. [5].

therefore be calculated from the toolpath. At this contact point if the region of the sheet where $r < r_{tool}$ undergoes a rigid body translation Δ_{OI} ($<\Delta y$) in the negative Z direction (Fig. 2a) then the value of Δ_{OI} is calculated as

$$\Delta_{OI} = \Delta y - \left(\frac{L}{\gamma}\right)\left(1 - \frac{2[E(R) - E(\varphi_0, R)]}{K(R) - F(\varphi_0, R)}\right) \tag{1}$$

where γ is a constant (to be calibrated) and L is measured along the profile of the n^{th} shape from the projected point to the base of the n^{th} shape (Fig. 2). $E(R)$ and $K(R)$ are complete elliptic functions of the first and second kind, respectively, $E(\varphi_0,R)$ and $F(\varphi_0,R)$ are incomplete elliptic functions of the first and second kind, respectively. The parameters R and φ_0 are obtained as

$$R^2 = \frac{1 + \sin\theta_{OI}}{2.0}, \qquad \varphi_0 = \sin^{-1}\left(\frac{1}{\sqrt{2}R}\right) \tag{2}$$

The value of θ_{OI} at each contact point on the $(n + 1)^{th}$ shape is computed using Eq. (3) based on Cui et al. [10],

$$\tan\theta_{IO} = \frac{\sin\theta_1}{((L\,\Delta x/\gamma) + \cos\theta_1)} \tag{3}$$

where $\Delta x = S[\sin(|\theta_2 - \theta_1|)/\sin(\theta_1)]$ and S is the length of $(n + 1)^{th}$ shape's profile measured from the contact point to the top of the $(n + 1)^{th}$ shape, as shown in Fig. 2a. Both S and L are measured along the profiles of the corresponding shapes to take into account the fact that the profiles of the intermediate shapes to be formed might not always be a straight line. θ_2 and θ_1 are the ideal wall angles at the contact point on the $(n + 1)^{th}$ shape and at the corresponding projected point on the n^{th} shape respectively (Fig. 3). Physically, at any contact point on the $(n + 1)^{th}$ shape, Δy corresponds to the displacement and θ_{OI} corresponds to the angle at the loading end of the modified cantilever beam (Fig. 3). At any contact point, since L, S, θ_2 and θ_1 are known from the toolpath, the value of θ_{OI} is obtained using Eq. (3). This θ_{OI} is then used in Eq. (2) to find the values of R and φ_0, which are then used to find Δ_{OI} from Eq. (1). During the OI toolpath, contact between the tool and the sheet at any instant may

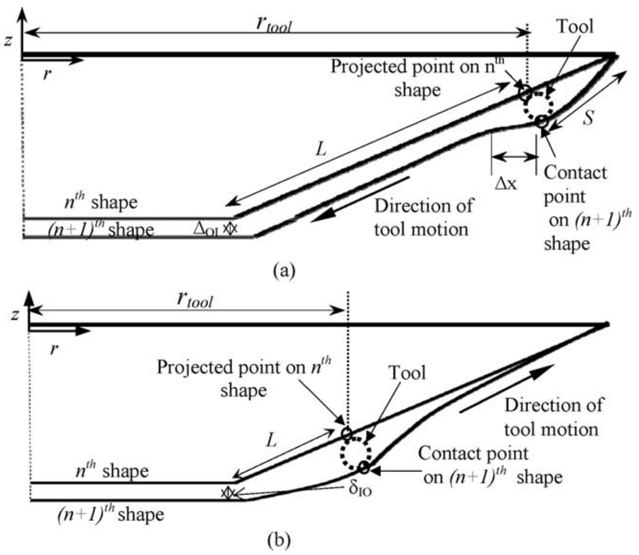

Fig. 2. Schematic representation showing (a) OI toolpath and (b) IO toolpath.

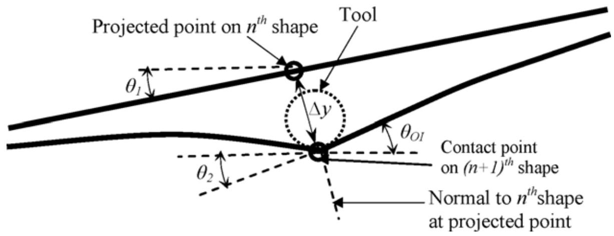

Fig. 3. Close up view of the tool contact area at any point during the deformation of the $(n + 1)^{th}$ shape.

be lost due to prior rigid body translation. Consequently there will be no increase in rigid body translation at this particular moment. To incorporate this phenomenon in our calculation, at any contact point the accumulated Z coordinate of the current contact point is calculated and compared to the ideal Z coordinate from the CAD model. If this accumulated Z coordinate at the n^{th} shape is lesser than its ideal Z coordinate in the $(n + 1)^{th}$ shape, then contact is lost in the next cycle and the corresponding Δ_{OI} is the same as the current value.

2.2. Modelling rigid body translation in IO toolpath

The incremental rigid body translation of the base for the IO toolpath, δ_{IO} (Fig. 2b), is assumed to be a power law function of L (Fig. 2b) and θ_{IO}, as shown in Eq. (4)

$$\delta_{IO} = \left(\frac{\Delta y}{L^a}\right)\theta_{IO}^b \tag{4}$$

where a and b are constants (to be calibrated). The value of θ_{IO} in Eq. (4) is calculated as

$$\theta_{IO} = |\theta_2 - \theta_1| \tag{5}$$

where θ_2 and θ_1 are obtained at any contact point as described in Section 2.1. At any contact point on the $(n + 1)^{th}$ shape the values of L (Fig. 2b) and Δy (Fig. 3) are also obtained as described in Section 2.1. In contrast to Eq. (1), which is an absolute formulation for the rigid body translation, the total rigid body translation for the IO toolpath, Δ_{IO} is obtained as a summation of the incremental rigid body translations as shown in Eq. (6), where N is the number of contact points along the profile of the $(n + 1)^{th}$ shape.

$$\Delta_{IO} = \sum_{i=1}^{N} (\delta_{IO})_i \tag{6}$$

2.3. Calibration and validation

The constants γ, a, b in Eqs. (1) and (4) were calibrated using three dimensional ABAQUS implicit simulations in which the blank was discretised with linear shell elements. The blank material used in simulations and in subsequent experiments was 1 *mm* thick AA5052 sheet. The components formed were the cap of a sphere as the final shape with a cone as the first shape (Fig. 4a). Both purely OI and purely IO toolpaths were simulated for the second shape using tool diameters of 5.0 *mm* and 10.0 *mm* respectively, so that

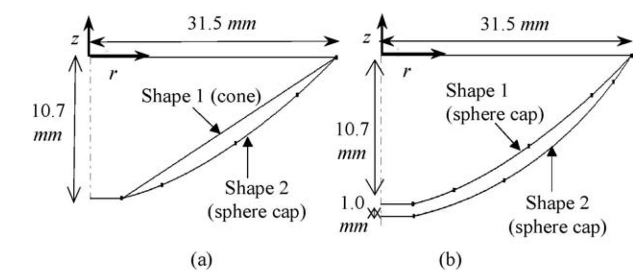

Fig. 4. Component shapes for (a) Case 1 and (b) Case 2, used to calibrate and validate the developed analytical models.