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Technical paper

Analytical prediction of stepped feature generation in multi-pass single point incremental forming

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ABSTRACT

Single point incremental forming (SPIF) is a new sheet metal forming process characterized by higher formability, product independent tooling and greater process flexibility. The inability of conventional single pass SPIF to form vertical walls without failure is overcome by forming multiple intermediate shapes before forming the final component, i.e., multi-pass single point incremental forming (MSPIF). A major issue with MSPIF is significant geometric inaccuracy of the formed component, due to the generation of stepped features on the base. This work proposes analytical formulations that are shown to accurately and quantitatively predict the stepped feature formation in MSPIF. Additionally, a relationship is derived among the material constants used in these analytical equations, the yield stress and thickness of the blank material, such that the computational effort required for the calibration of these constants can be minimized. Finally, the physical effects of yield stress and sheet thickness on the rigid body translation are further discussed.

1. Introduction

Single point incremental forming (SPIF) is a die-less sheet metal forming process in which a peripherally clamped sheet is locally deformed using a simple hemispherical ended tool moving along a predefined toolpath. The cumulative effect of these local deformations leads to the desired final geometry. Since the tooling is not product shape specific, SPIF has greater process flexibility and significant potential to reduce the costs in prototyping and small batch production. Additionally, SPIF requires lesser forming force compared to conventional sheet metal forming processes. This reduction in forming force allows the usage of smaller and more mobile machines. Furthermore, it has been noted that conventional forming limit diagrams (FLDs) were not appropriate to evaluate the blank formability in SPIF [1–4]. Enhanced blank formability in SPIF as compared to conventional forming has the ability to reduce the weight of formed components. The increased through-thickness shear is the reason for increased formability in SPIF as compared to conventional forming [1,2]. Malhotra et al. [3] indicated that greater shear in SPIF cannot be held as the only reason for formability improvement and proposed a so-called 'noodle theory' to explain the increased formability in SPIF. In this theory, the local nature of deformation is the primary reason for increased formability in SPIF as compared to conventional forming. Therefore, a new representation of forming limits for SPIF related to process variables (feed rate and tool radius, etc.) and part geometry (part slope and part curvature radius, etc.) was developed [4]. Due to these advantages, SPIF has found numerous potential applications in the automotive [5], aerospace [6] and biomedical [7] manufacturing sectors.

Conventional single-pass SPIF forms components in one step, i.e., without forming any intermediate shapes. One of the main issues in single-pass SPIF is that components with steep walls, such as a 90° wall angle, cannot be formed without failure. For example, the maximum formable wall angle for most steel and aluminum alloys is about 60–70° for blank thicknesses ranging from 0.8 mm to 1.5 mm [8,9]. While a smaller incremental depth can enhance the formability, geometry accuracy and the surface finish [6,10], the forming time is simultaneously increased. Malhotra et al. [11] proposed an automatic 3D spiral toolpath generation method for SPIF using local geometry dependent incremental depth to minimize the forming time while satisfying user constraints on geometry accuracy and surface finish. However, this methodology did not account for formability as a constraint for generation of optimum toolpaths.

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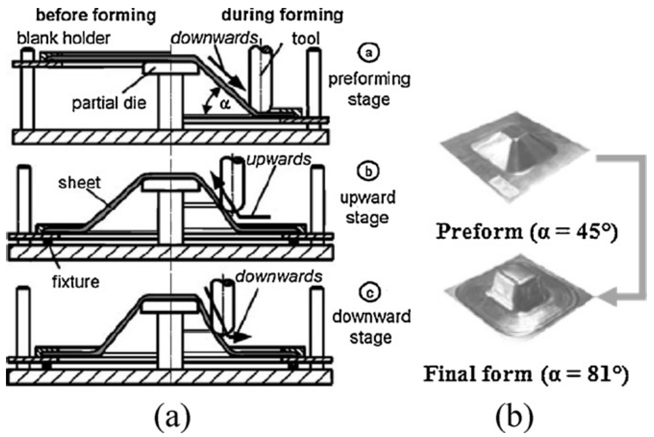

Fig. 1. Multi-pass toolpath strategy in TPIF and the corresponding formed component without stepped features on the base: (a) multi-pass strategy. (b) Preformed and final four-sided pyramid with $\alpha = 81^\circ$ [13].

Multi-pass single point incremental forming (MSPIF) increases the maximum formable wall angle in SPIF by forming multiple intermediate shapes before forming the final component. Additionally, MSPIF creates the potential to control the spatial thickness distribution of component. This makes it possible to form a part with thinner sheets while satisfying the required structural integrity in key locations. Therefore, toolpath generation in MSPIF has attracted considerable interest in the sheet metal forming community. Kim and Yang [12] used a double-pass forming method to form an ellipsoidal cup and a clover shaped cup. It was found that the formability was improved with a more uniform thickness strain distribution of the final shapes. A four-sided pyramid with an 81° wall angle was formed using two point incremental forming (TPIF) with a multistage toolpath strategy [13]. The sheet was performed into a shallow shape with a 45° wall angle and then 7–12 stages were subsequently formed in which the pitch motion of the forming tool alternated from upward to downward, as shown in Fig. 1a. There were no stepped features on the base of the formed component because a partial die was used during the forming (Fig. 1b). Note that the use of a partial die leads to a loss of the inherent flexibility of the SPIF process. Skjoedt et al. [14] formed a circular cylindrical cup with a 90° wall angle using down-up-down-down (DUDD) and down-down-down-up (DDDU) toolpath strategies, as shown in Fig. 2a. They showed that the DUDD strategy resulted in fracture in the transition zone between the base and the side wall (Fig. 2b). Duflou et al. [15] used MSPIF to redistribute the material from the previously unformed base of the component to the side wall and formed vertical walls without part failure (Fig. 2c). Based on the obtained material flow trajectories from FEA, it was shown that material movement between two consecutive intermediate shapes was in a direction normal to the former intermediate shape (Fig. 2c). While the formability was increased with strategies used in Refs. [14] and [15], a significant drawback was the generation of stepped features on the base of formed components (Fig. 2b and d). These stepped features cause unacceptable geometric inaccuracy of the formed components.

Malhotra et al. [16] pointed out that in aforementioned toolpath strategies a rigid body translation of the base occurred during the forming of each intermediate shape. It was shown that the stepped features were caused by accumulation of rigid body translation of the base during forming of multiple intermediate shapes. They proposed analytical formulations for calculating this rigid body translation and created a mixed toolpath strategy that prevented the generation of stepped feature in MSPIF (Fig. 3). In these analytical formulations used for the calculation of rigid body translations, three material constants were needed to calculate the rigid body translation. These constants were calibrated manually by matching the analytical predictions of rigid body translation with those from FEA. This manual calibration was essentially a repetitive trial and error process. Therefore, when the blank material or thickness changes, it becomes necessary to recalibrate the material constants using additional time consuming simulations. To reduce the needs of time-consuming simulations for calculating the rigid body translation in generating the mixed toolpath, an analytical model has been established to predict the rigid body translation when new blank material or sheet thickness is applied.

This work is an extension of work published by this group [16] to remove the aforementioned issue by relating the material constants used in analytical formulations to the yield stress and the sheet thickness of the blank. First, the analytical models used for cal-

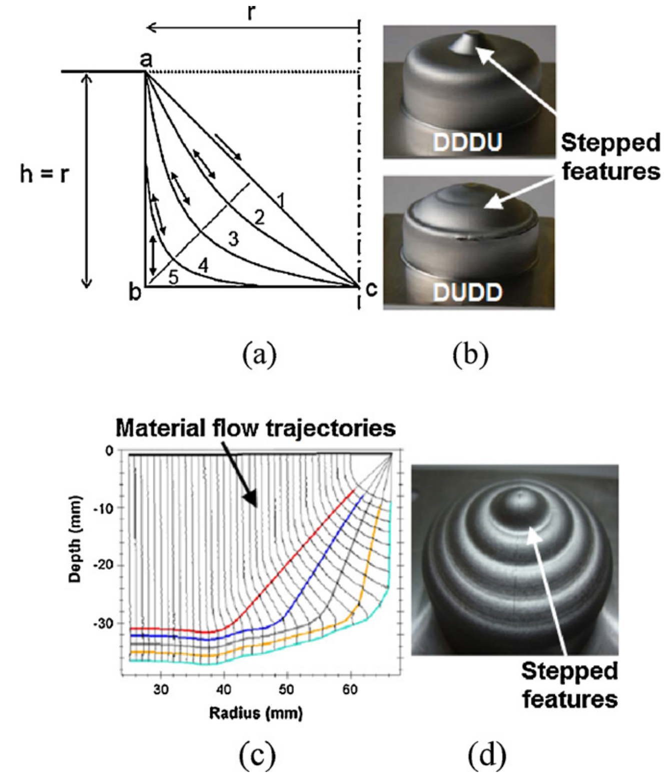

Fig. 2. MSPIF toolpath strategies and the corresponding formed components with stepped features on the base: (a) and (b) Skjoedt et al. [14] (c) and (d) Duflou et al. [15].

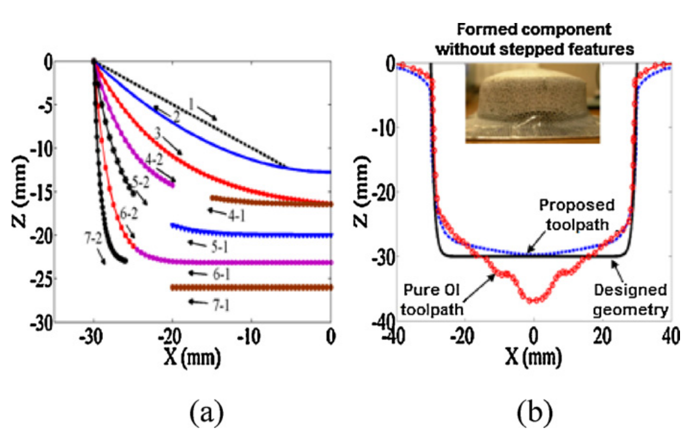

Fig. 3. (a) Toolpaths used to form cylinder with mixed toolpath strategy (b) comparison of formed cylinder profiles using mixed toolpath and pure OI toolpath, with the designed profile geometry [16].