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Experimental and numerical investigation on incremental sheet forming with flexible die-support from metallic foam

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ABSTRACT

Poor geometric accuracy of workpieces plagues single-point incremental forming (SPIF) due to lack of support and unwanted plastic deformation. In this work, metallic foam blocks are used as flexible die-support in duplex (or two-point) incremental forming (DPIF), and the geometric accuracy of workpieces is significantly improved by comparing to single point incremental forming as well as other improved strategies as demonstrated through both finite element simulation and experiments. Since the metallic foam is plastically deformable and easy to machine (or cut) and has a certain strength, DPIF with flexible die-support (DPIF-F) improves geometric accuracy but also maintains the flexibility of incremental sheet forming.

1. Introduction

Incremental forming (IF) has attracted great and increasing interest in producing sheet metal products in the past two decades, due to the absence of the specific tooling, high flexibility, and greater formability compared to conventional stamping process. In single-point incremental forming (SPIF), a spherical headed tool deforms a peripherally clamped sheet blank with pre-defined tool path and eventually forms the final geometry. Geometric accuracy is the main issue having been plaguing SPIF since its first appearance, which can result from lack of support (especially in the flange region), springback due to retreating the forming tool and unclamping the sheet specimen [1], low stiffness of the incremental forming machine or robot, twist [2].

In recent years, many efforts have been devoted to improve geometric accuracy of sheet metal products by some variants of incremental forming. Two-point incremental forming (TPIF) utilizes a specific rigid die (or a partial rigid die, Fig. 1a) below the sheet to provide support and therefore to increase geometric accuracy [3–6]. However, the specific rigid die is dependent on the part geometry and TPIF loses flexibility to a certain extent. Instead of utilizing a specific/partial rigid die, double-sided incremental forming (DSIF) [7] uses a spherical headed tool (hereafter designated as supporting tool) locally contacting with the sheet on its two sides along with the forming tool as shown in Fig. 1b, which is also known as duplex incremental forming with local support (DPIF-L) [8]. DSIF significantly improves the geometric accuracy in the wall region of the part and also in the flange region with some additional measure, e.g. multi-pass forming, tool path optimization etc.; furthermore, attributed to the superimposition of compression by the supporting tool, formability of sheet metals can be further increased in DSIF [8]. Another variant of duplex incremental forming to improve geometric accuracy in the flange region is DPIF-P (refer to Fig. 1c) reported by Kreimeier et al. [9], where the supporting tool provides peripheral support and moves only in a pre-defined plane but synchronically with the forming tool. A hybrid method of combining stretching and IF was developed by Hirt et al. [10] to increase geometric accuracy as well as to shorten forming time of parts with complex profile. Prof. Cao's group proposed an accumulative-DSIF (ADSIF) strategy [11,12] to enhance geometric accuracy, which forms the deepest feature of the part first and takes the advantage of rigid-body motions. The geometric accuracy was reported that it depended on the incremental depth of the tool path in ADSIF by Malhotra et al. [11], where a smaller geometric error resulted from applying a smaller incremental depth. The potentials of DSIF is enhanced by ADSIF. Additionally, other strategies were also developed through multi-pass forming [9,13,14] and optimizing tool path using closed-loop control [15], multivariate adaptive regression splines [16], a response surface methodology [17], an artificial cognitive system [18], etc. For hard-to-form materials, heat-assisted IF (either SPIF or DSIF) is also a solution to reduce springback due to reduced forming forces at elevated temperatures [19].

In this work, a strategy is proposed to improve geometric accuracy of parts by DPIF, in which metallic foam is used as flexible die-support below the sheet. Both finite element simulation and

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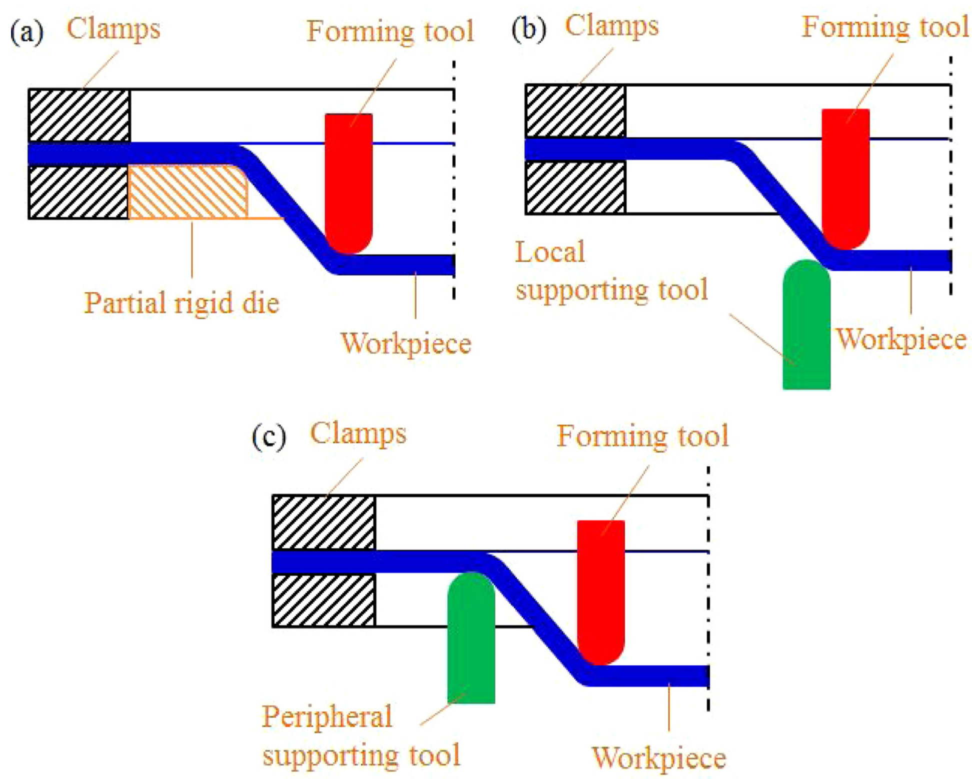

Fig. 1. Duplex (or two-point) incremental forming with (a) a partial rigid die (DPIF-R), (b) local support (DPIF-L) and (c) peripheral support (DPIF-P).

Table 1
Mechanical properties of the mild steel DC04.

n-value	k-value	ε_0-value	r_0	r_{45}	r_{90}
0.230	531	0.0045	2.58	1.92	2.19

Note: n, k and ε_0-values are the parameters in the Swift law $\sigma = k(\varepsilon_p + \varepsilon_0)^n$, where σ and ε_p are true stress and plastic strain, respectively. r_0, r_{45} and r_{90} are Lankford coefficients.

experiments are carried out to validate the proposed strategy, which is hereafter designated as DPIF-F. The flexibility and possibility of combining the flexible die-support with other strategies in literature are discussed.

2. Experimental details

The used sheet material was 0.8 mm thick mild steel DC04. Its mechanical properties are listed in Table 1. The steel blank size was 250 mm × 250 mm, and it was peripherally clamped throughout incremental forming experiments leaving a square forming area of 220 mm × 220 mm. SPIF and DPIF (DPIF-L and DPIF-F) were performed on the Roboforming system developed at the Ruhr-Universität Bochum, where the forming tool and the supporting tool (if necessary) were held by a master and a salve KUKA KR 360/1 robot, respectively. (Details refer to [8].) A spherical headed tool, which was the same as the forming tool having a radius of 6 mm, was utilized in DPIF-L. The paths of the forming and supporting tools were generated by using CAMWorks software and a self-developed Matlab code, which are spiral with an incremental depth (z) of 0.5 mm. The forming tool speed was set to 25 mm/s, and oil was applied as lubricant only to the sheet surfaces which had contact with the forming or supporting tool in all experiments. The metallic foam used in DPIF-F was made from aluminum. Fig. 2 presents the nominal yield stress vs. volumetric strain curves of two Al foams with densities of 0.25 g/cm^3 (A) and 0.75 g/cm^3 (B) from

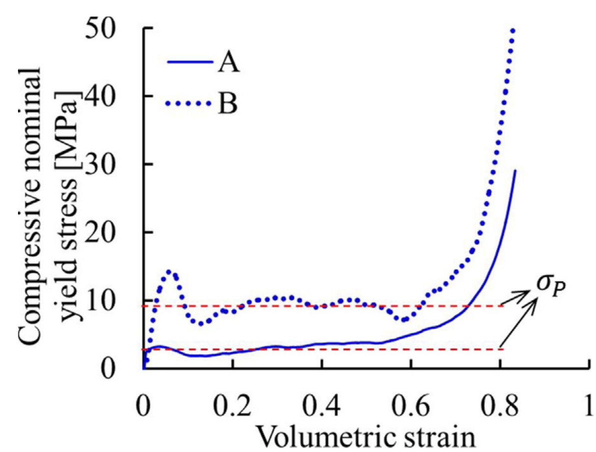

Fig. 2. Stress vs. strain curves of the used Al foams.

compression tests, where typical stress plateaus (or nominal yield strength, σ_P) at ~3.2 MPa (A) and ~9.7 MPa (B) were observed.

After retreating the tool(s), the 3D geometries of specimens were measured using a 3D optical measurement system Steinbichler COMET 5 2 M. Therefore, the geometric measurement considered the springback due to retreating the tool(s), but did not take into account the springback caused by unclamping the specimen.

3. Finite element model

Accurate finite element (FE) simulation helps to reduce experimental work and save time for optimizing forming processes. In this work, FE models were built for both SPIF and DPIF in the LS-DYNA, where the tools, clamping system and backing plates shown in Fig. 1 were regarded as rigid bodies. It is noted that the LS-DYNA was used