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To cite this article: D Morales-Palma *et al* 2018 *J. Phys.: Conf. Ser.* **1063** 012183

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Numerical study on the thickness homogenization in hole-flanging by single-point incremental forming

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Abstract. Incremental sheet forming is a novel technology that has significant benefits compared to conventional forming. However, it is a time-consuming process that is usually carried out in several forming stages to homogenize deformation and avoid material failure. In hole-flanging operations by SPIF, a single-stage strategy might provide functional flanges in considerably less time, however a non-uniform thickness is obtained along the flange. This work proposes a two-stage process as the best strategy to increase production rate, and an optimization methodology to produce a homogeneous thickness distribution of the flange. The procedure is used to automate the design process of parts and tool trajectories by CAD/CAM, and validate the optimal forming strategy by FEA.

1. Introduction

Hole-flanging is a forming process mainly used to manufacture circular flanges. There are many industrial applications of this process such as strengthening the edge of a hole, improving its appearance or providing additional support for joining sheet parts to tubes. Given its practical interest, recent research focuses on carrying out this process through single-point incremental forming (SPIF) [1–5]. SPIF is a novel technology that has been used for the last few years to obtain a variety of industrial parts due to its benefits compared with conventional sheet forming processes [6,7]. In circular hole-flanging by SPIF, a sheet with a pre-cut hole is deformed progressively and locally using a spherical forming tool controlled by a CNC machine-tool to produce a smooth round flange.

A drawback of incremental sheet forming processes is that part geometry and sheet thickness distribution are highly influenced by the tool path. Some authors have investigated different multi-stage strategies by programming simple part shapes for the intermediate stages [1–4,8,9]. In a recent paper, present authors presented an experimental study on the maximum flange that can be successfully formed by SPIF in a single stage [5]. This single-stage process leads to a great reduction of time, however it produces a non-homogeneous profile along the flange height. Subsequent studies of this process have addressed the sheet failure by performing a numerical analysis [10] and a preliminary study of the ideas developed in this paper [11].

The aim of this work is to propose an optimized hole-flanging process by SPIF in two stages, in order to homogenize the thickness distribution of the formed flange and reduce the manufacturing time. A simple optimization procedure is used to automate the workpiece design between stages,

the CNC code generation for the forming tool path, the analysis by FEM of resulting strains along the flange and the validation of the optimal forming strategy.

2. Background

Incremental sheet forming usually aims to homogenize deformation of the sheet part and avoid material failure by performing several forming stages. Different multi-stage forming strategies for SPIF have been investigated by some authors to achieve successful hole-flanging operations. Cui and Gao [1] experimentally analysed the thickness distribution along the sheet flange by developing three multi-stage strategies based on intermediate cylindrical and conical sheet pieces. Similar strategies were selected by Bambach et al. [3] for evaluating the maximum hole expansion ratio and geometrical accuracy of a mild steel sheets.

A drawback of multi-stage SPIF processes is that they are time-consuming. One way to reduce manufacturing time considerably is performing the forming process in a single stage. In a recent work, present authors investigated this idea and carried out an experimental study about hole-flanging process by SPIF in a single stage [5, 12]. Figure 1 presents the experimental setup, a schema of the helical tool trajectory and two tested specimens. The successful specimen corresponds to the limiting diameter (d_0) of the circular pre-cut hole of the blank sheet. The second specimen, with a smaller value of d_0, failed by fracture in the wall before finishing the piece, as can be seen in Figure 1(c).
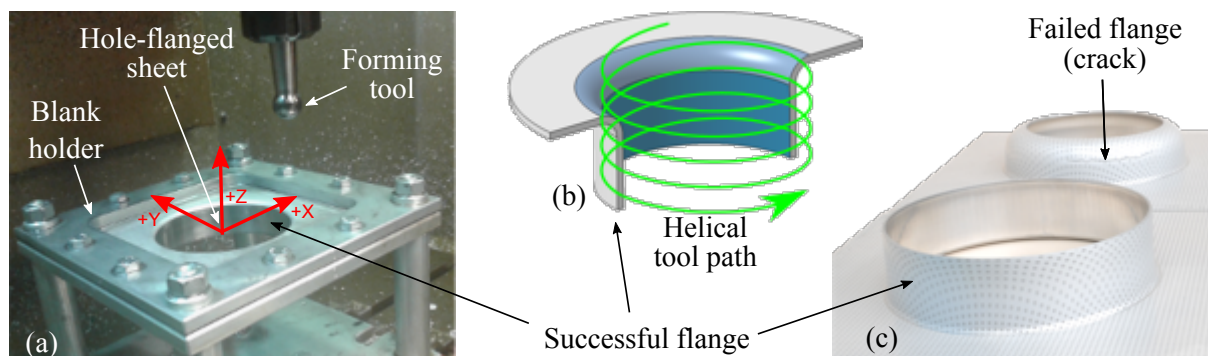

Figure 1. Hole-flanging by SPIF process in a single stage: (a) experimental setup; (b) cylindrical helical trajectory; (c) experimental specimens.

A single-stage process is the fastest strategy to produce hole flanges by SPIF, however it produces a non-homogeneous profile along the flange as reported in [5]. The idea proposed in this paper is to homogenize the flange deformation by designing a customized two-stages process based on previous studies.

3. Methodology

The proposed methodology aims to design and optimize a two-stage SPIF process for hole-flanging based on the deformation analysis of the same process but in a single stage.

The first step of the methodology is to analyse the flange thickness of specimens tested by the single-stage SPIF process [5]. As experimentally observed, there are three differentiated zones along the final flange: (1) a zone near the flat undeformed sheet; (2) an intermediate zone, where the thickness is smaller and the sheet tends to fail, as can be seen in the fractured specimen in Figure 1(c); and (3) the edge zone. Thus, the main objective is to control the deformation process of the intermediate zone or critical zone.

The proposed solution consists of applying a lower pressure with the forming tool in the critical zone. In the single-stage process, when the tool is near the critical zone, the edge zone is being radially expanded and performs a significant resistance to deformation. In this situation, the first stage of the two-stage SPIF process has been designed to modify the flat shape of the edge zone in order to reduce its resistance. This can be carried out by decreasing the diameter of the helical path of the tool, as illustrated in Figure 2. As can be seen, the proposed intermediate piece at the end of the first stage consists of an initial cylindrical surface followed by a conical surface to relax the pressure over the critical zone and a cylinder with a smaller diameter for the edge zone. In the second stage, the helical path follows a simple cylinder of final diameter d_f to form the preformed piece.
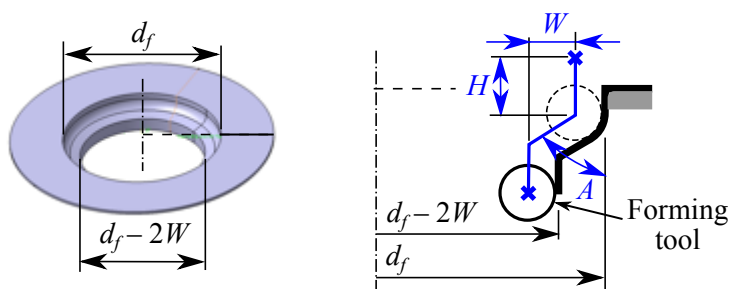

Figure 2. Geometrical parameters for the first stage of the proposed hole-flanging process by SPIF in two stages.

Three parameters have been used to characterize the tool trajectory for the first stage, as represented in Figure 2: a height H for the first cylindrical helical path, a slope A for the intermediate conical helical trajectory, and a gap W between the final cylindrical helical path and the first one. The section profile of the deformed sheet is obtained by compensating the tool geometry of radius R, represented as a circumference in Figure 2.

A numerical study of the proposed hole-flanging process by SPIF in two stages has been developed to find the optimal values of parameters H, A and W in order to homogenize the sheet thickness. The model for the proposed two-stages process has been developed using the same sheet geometry, forming tool and setup parameters of a successful experimental hole-flanging test by SPIF in a single stage developed in previous studies [5, 12]. The selected experimental test was carried out using a tool radius $R = 6$ mm to deform a 7075-O aluminium alloy of 1.6-mm thickness and initial hole diameter $d_0 = 64.5$ mm to a final hole diameter $d_f = 95.8$ mm.

The parametrized geometry for both intermediate and final sheet pieces, as well as the tool trajectories, were modelled in CATIA V5. For the selected configuration of hole-flanged part, a series of 18 sets of consistent parameter values of A, H and W were chosen to perform the numerical study (see Table 1). To ensure the integrity of the proposed shape for the intermediate deformed sheet and avoid inconsistent situations in the generation of tool trajectories, the CAD model included some dimensional constraints for parameters, as reported in [11]. Thus, the following values were set for parameters: $A = 30°$ (steep slope), $45°$ (medium slope) and $80°$ (soft slope); 3 representative values for H (mild, medium and deep height) which depend on the A value; and up to 3 values for W (large, medium and small gap) depending of the values of the above parameters.

A series of CATIA scripts were programmed to automate the whole process of CAD modelling, trajectories calculation and CNC programs generation for every set of parameters A, H and W. The generated CNC code aimed to simulate the movements of the forming tool in a FE model in Abaqus. This FE model was also automated by a series of Python scripts in order to calculate the process variables as sheet thickness of the final flange, and extract data and some model snapshots from the results data file.

Table 1. Set of values for parameters A, H and W.

A °	H mm	W mm	A °	H mm	W mm	A °	H mm	W mm
30	7	1	45	7	2	80	7	6
30	7	3	45	7	5	80	7	8
30	7	6	45	7	8	80	7	11
30	12	1	45	11	2	80	10	6
30	12	3	45	11	5	80	10	8
30	18	1	45	16	2	80	12	6

Table 2. Mechanical properties for AA7075-O sheets.

E (GPa)	ν	YS (MPa)	K (MPa)	n
65.7	0.3	109.7	314	0.13

As said before, the parametrized FE model was calibrated using the experimental results on previous studies [5, 12]. A Hollomon type law was used to characterise the hardening of the material. The mechanical properties of the AA7075-O are summarized in Table 2. The metal sheet was modelled with 2D shell elements as a circular ring partitioned by three concentric sectors. The exterior sector is clamped (by the backing plate and the blank holder) and the central sector is vertically hold (on the backing plate). The size of the mesh was defined finer near the pre-cut hole. It has approximately 12000 elements, 360 around the circumference and about 0.8 mm in size on the inner edge. As can be seen in Figure 3, a duplicate tool was modelled to save calculation time of the transition movement between both forming stages. A friction coefficient of 0.1 was used.
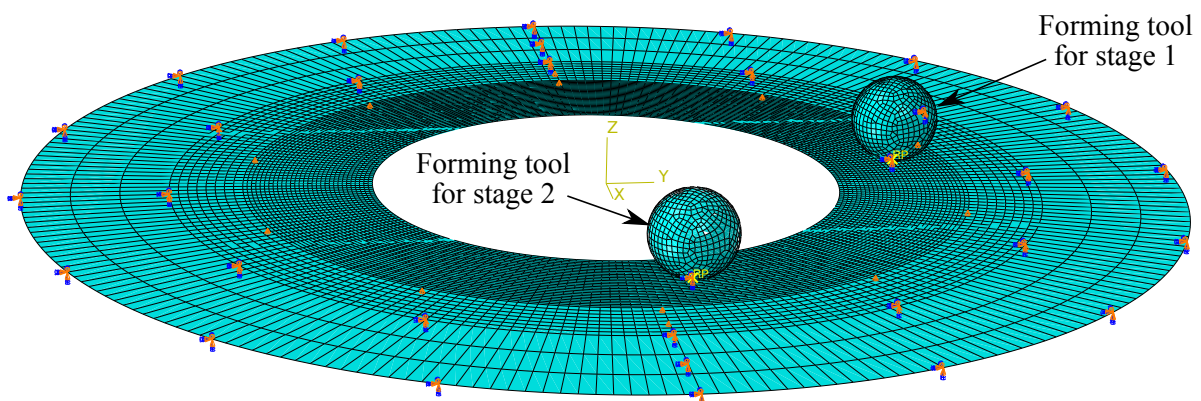
Figure 3. Detail of the finite element mesh and boundary conditions.

The main drawback of a previously developed FE model was their computing time that exceeded one month on a 64-bit PC with an Intel Core i7 processor and 32 GB of RAM. To

overcome this problem, the forming time was reduced by setting a stepdown of 0.5 mm/rev for simulated helical trajectories instead of 0.2 mm/rev used in the experiments. Furthermore, the tool feedrate (1 m/min) and the aluminium density (2.81 kg/cm^3) were scaled up by 10^2 and 10^4, respectively. These scale factors, which are typical in explicit solvers for quasi-static simulations, were found by trial and error until reaching a balance between computing time and simulation process stability.

4. Results

For each set of parameters in Table 1, the automated procedure by scripts produced a CNC program (APT code) for the first stage of the two-stages process by SPIF. Whereas a unique CNC program for the second stage was used in all simulations. APT code was automatically translated to the data entry format of Abaqus and the parametrized FE model was executed in batch mode. Figure 4 presents a sample of tool trajectories simulation and snapshots of the calculated sheet thickness distribution, for parameters $A = 80°$, $H = 7$ mm and $W = 6$ mm.
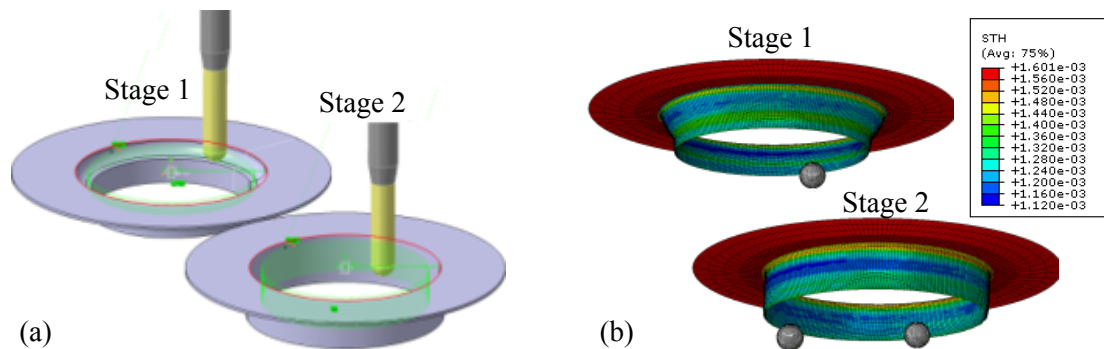

Figure 4. Simulations of a two-stages SPIF process for parameters $A = 80°$, $H = 7$ mm and $W = 6$ mm: (a) tool paths in CATIA V5; and (b) graphical representation for sheet thickness in Abaqus.
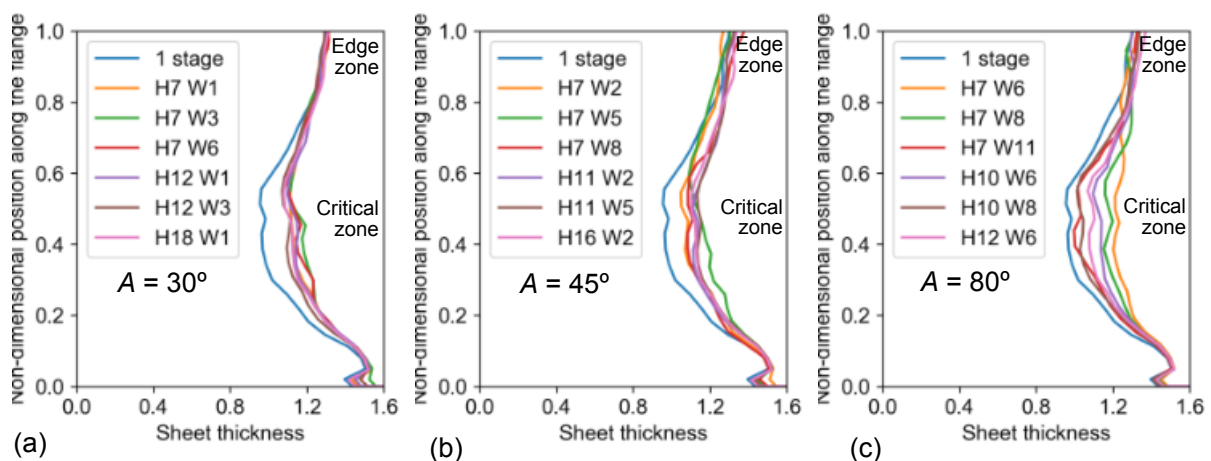

Figure 5. Thickness distribution of the SPIF process in one and two stages.

To analyse the process deformation along the sheet flange, a radial path following a node set was defined in Abaqus. Figure 5 presents three graphs with the thickness distribution of the final

flange along the radial path, for slope values $A = 30°$, $45°$ and $80°$. These graphs also include the thickness distribution for the simulated single-stage process by SPIF, referred to as '1 stage' in legends. It should be highlighted that this thickness profile reproduces well the tendency of experimental results, as can be consulted in [5]. Indeed, the higher thickness reduction occurs in the intermediate zone or critical zone, as described below.

As seen in Figure 5, all simulations of the proposed two-stages process improve the thickness distribution compared to the SPIF process in a single stage. That is, the material deformation is more homogeneous and the thickness reduction is diminished, especially in the critical zone. Figure 5(a-b) reveals that all thickness predictions are similar for steep and medium slopes. However, using a soft slope ($A = 80°$), the other parameters have a great influence on thickness reduction so that the most homogeneous sheet thickness distribution was found from the smaller values of both height ($H = 7$ mm) and gap ($W = 6$ mm).

5. Conclusions

This work presents a numerical study on the homogenization of sheet thickness in a hole-flanging process by SPIF. A customized two stages process has been proposed based on previous experimental studies. The main conclusions of this work can be summarised as follows:

- An automated optimization procedure based on CAD/CAM and FEA software tools has been successfully applied to evaluate the viability of the proposed process by SPIF.
- The proposed hole-flanging process by SPIF in two stages reduces considerably the fabrication time compared to the multi-stage processes proposed in the literature.
- The proposed two-stages process appreciably improves the homogenization of the thickness distribution along the flange in comparison with a single-stage process.
- In the authors opinion, above conclusions are valid for a general hole-flanging operation by SPIF. For geometries and materials other than those analysed in this study, the same automated procedure would allow the A, H, W parameters to be optimized again.

Acknowledgments

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