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Preliminary investigation on homogenization of the thickness distribution in hole-flanging by SPIF

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Abstract

A drawback of the hole-flanging process by single-stage SPIF is the non-uniform thickness obtained along the flange. Multi-stage strategies have been used to improve it, however they increase notably the manufacturing time. This work presents a preliminary study of the tool paths for a hole-flanging process by SPIF in two stages. An intermediate geometry of the piece is proposed from the analysis of the thickness distribution observed in previous single-stage process. A simple optimization procedure is used to automate the intermediate part design, the NC code generation for the tool path and the validation of the optimal forming strategy by means of FEA.

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Keywords: Hole flanging; Incremental sheet forming; Two-stage SPIF

1. Introduction

Single-point incremental forming (SPIF) is a novel technology that makes use of a hemispherical tip tool to locally and progressively shape a sheet, frequently using a NC machine-tool. The paper by Jeswiet et al. [1] describes exhaustively the genesis, development and applications of SPIF. SPIF has been used for the last decade to obtain a variety of industrial parts due to its benefits, such as non-dedicated equipment requirements, dieless process, flexibility,

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low costs, etc. Besides, its main benefit is the enhancement of sheet formability compared to conventional processes [2,3].

In circular hole-flanging by SPIF, a clamped sheet with a pre-cut hole is deformed progressively and locally using a spherical tip tool controlled by a NC machine-tool to produce a smooth round flange. The material is mainly deformed by a combination of bending and stretching.

Some authors have investigated the capability of SPIF to successfully perform hole-flanging using different multi-stage forming strategies. Cui and Gao [4] presented an experimental study of three multi-stage strategies, comparing the Limit Forming Ratio (*LFR*) as a measure of material formability and thickness distribution along the flange in each case. In a later work, Centeno et al. [5] studied experimentally the combined influence of pre-cut holes and tool path forming strategies on the deformation mechanics of hole-flanges, by producing intermediate conical parts of increasing angle. Following similar forming strategies, Bambach et al. [6] accelerated the process by using a rotating tool set on which the forming tool was displaced radial and axially. A common characteristic of these studies is the simplicity of the proposed shape for the intermediate sheet parts between stages, most often using straight section parts.

Multi-stage strategies are time-consuming and, according to the geometrical and surface constraints of the part, the number of stages for obtaining a fully functional piece can be minimized. In a recent work, present authors experimentally investigated the maximum flange that can be successfully formed by SPIF in a single stage [7,8]. Assuming its geometrical restrictions, a single-stage strategy might provide functional flanges in considerably less time.

Other works have focused on studying more complex multi-stage SPIF strategies to better extend deformation to the regions of the blank. Skjoedt et al. [9] proposed a five-stage strategy to form cylindrical cups with vertical walls. The strategy consists of forming a first conical cup with a taper angle in the first stage, followed by subsequent stages that progressively move the conical shape towards the desired cylindrical geometry, with the tool moving either downwards or upward. Mirnia et al. [10] studied the effect of various deformation paths on the thickness distribution. Authors proposed a three-stage strategy in SPIF to form truncated cones that improves significantly the sheet thickness compared to cones formed by a single-stage and a conventional three-stage strategy.

This work presents a preliminary study of the tool path optimization for a hole-flanging process by SPIF in two stages, in order to homogenize the thickness distribution of the flange and reduce the manufacturing time. The parameterised geometry of the intermediate piece is proposed from the analysis of the thickness distribution in previous studies. A simple optimization procedure is used to automate the intermediate part design, the NC code generation for the tool path and the validation of the optimal forming strategy by means a numerical analysis by FE.

2. Hole-flanging by SPIF in a single stage

Present authors recently developed an experimental study on the hole-flanging by SPIF process in a single stage [7,8]. The objectives of this work were to analyse the physical mechanisms controlling the sheet failure during this forming process and to obtain the maximum flange that can be successfully formed by SPIF in a single stage. To this end, a series of experimental tests on AA7075-O metal sheets of 1.6 mm thickness were performed and analysed.

The single-stage hole-flanging tests were carried out on a 3-axis milling CNC machine. The experimental setup is shown in Fig. 1(a). The SPIF setup comprised a blank holder and a backing plate with a 100-mm diameter hole, both fixed to the machine table through a rigid rig. The sheet metal blanks with different pre-cut holes were fixed by the holder over the backing plate and were incrementally deformed by a hemispherical tip tool. To analyse the effect of the sheet thickness to tool radius ratio on formability, three different radii were used (6, 8 and 10 mm). Two tool rotation conditions were tested, 0 rpm (locked tool) and 1000 rpm clockwise. The feed rate was set to 1000 mm/min. The friction effects were minimised by using a special lubricant for metal forming applications. To study the deformation and failure mechanisms, the forming forces were measured during the tests and the strains at the outer sheet surface were obtained using circle grid analysis. The flange height, thickness profile along the flanges and surface roughness were analysed on the final parts.

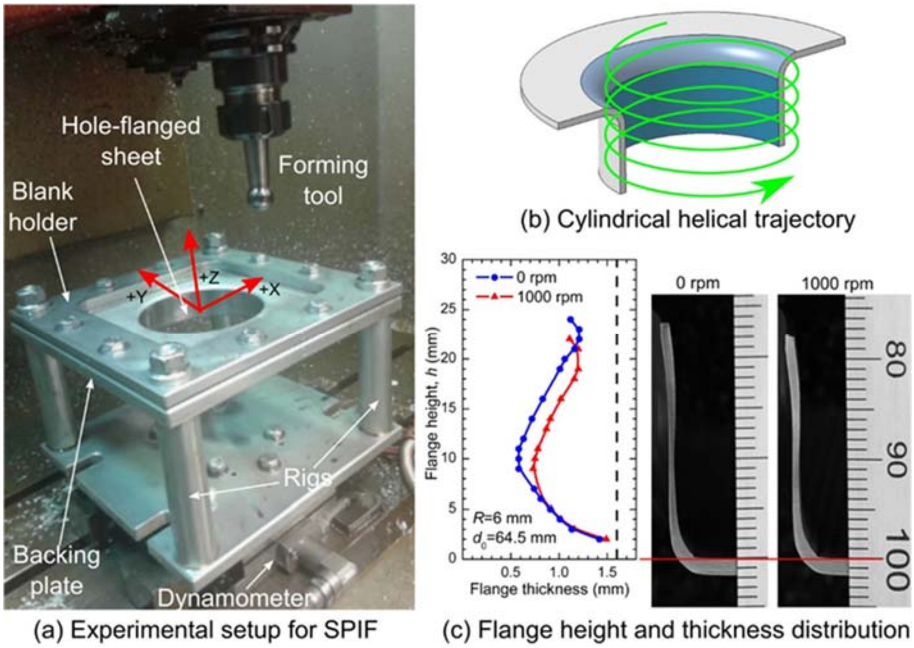

Fig. 1. Schema of the hole-flanging by SPIF process in a single stage.

A series of pre-cut holes was machined on the sheet blanks to obtain the formability limits of the single-stage process with values varying from 55 to 82 mm. The inner diameter of the final cylindrical hole was designed to 95.8 mm. The forming trajectories to perform the hole-flanging tests were modelled and simulated in CATIA V5 using the machining workbenches. A cylindrical helical anticlockwise trajectory was programmed, as represented in Fig. 1(b). The step down was 0.2 mm/turn.

Fig. 1(c) presents the thickness profile along the flange obtained in two hole-flanging tests at 0 and 1000 rpm, respectively. The results correspond to tests performed with a 6-mm radius tool in blanks with a 64.5-mm diameter hole. As can be observed, thickness reduction presents a wavy profile along the flange height, with a maximum reduction of 62% (0 rpm) and 53% (1000 rpm) around the middle of the flange. Experimental results of multi-stage hole-flanging noted by Cui and Gao [4] present a similar evolution in thickness distribution by forming successive conical frustum of increasing angle up to 90°.

3. A proposal to homogenize the flange thickness in a two-stage SPIF process

As said before, a drawback of the hole-flanging process by SPIF in a single stage is that it produces a non-homogeneous profile along the flange. Multi-stage strategies in which specimens are formed progressively using simple part shapes between stages [4-6,9] have been recently explored. However, the gain in thickness uniformity is counteracted by a noticeable increase in manufacturing time. So, the minimization and/or optimization of the number of stages and the tool trajectories are crucial.

In the following, the design a two-stage SPIF process to homogenize the final thickness distribution is discussed. A preliminary optimization analysis of the geometry of the intermediate deformed sheet between both stages as a function of the tool stroke and position is presented.

In order to elucidate the optimized intermediate shape of the sheet for the two-stage process, an analysis of the flange thickness in the single-stage process has been performed at first. As can be observed in Fig. 1(c), there are three differentiated zones along the flange: (1) a zone near the flat undeformed sheet, whose thickness is progressively decreasing; (2) an intermediate or critical zone, where the thickness is smaller and the sheet failure tends to occur; and

(3) the edge zone, whose thickness is progressively increasing. The main objective is to control the deformation process of the intermediate zone. This can be achieved by performing a lower pressure with the forming tool in that zone.

In the single-stage process, when the tool is near the critical zone, the edge zone still retains a flat shape. The material is being radially expanded, performing a significant resistance of being deformed. This means that the diameter of the helical path of the tool should be decreased in order to relax the pressure over the critical zone.

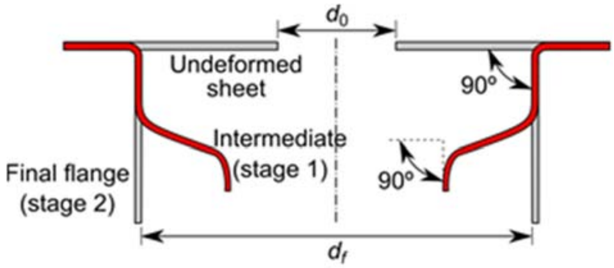

Fig. 2. Intermediate sheet section in the proposed hole-flanging by SPIF in two stages.

The proposed idea is schematically represented in Fig. 2. The slope of the sheet section decreases significantly from its initial value of 90° to relax the pressure over the critical zone. Once the critical zone has been overcome, the sheet slope can be maintained to the end, or it can be changed back to 90° as illustrated in Fig. 2.

The importance of the sheet shape near the edge produced at the first stage of the forming process can be explained as follows. From a geometrical point of view, a cylindrically shaped edge will offer less resistance to the forming of the critical zone in the second stage of the process than an edge with the original flat shape. On the other hand, if a cylindrical edge is formed in the first stage, instead of leaving it flat, the material will harden and provide more resistance during the second stage. Thus, the net final result will depend on the intermediate geometry of the sheet and the hardening characteristics of the material.

To evaluate the above ideas, a numerical study of the proposed hole-flanging process by SPIF in two stages is currently being developed. The study includes the calculation of the optimum geometry of the intermediate sheet to obtain a more homogeneous final flange thickness. The proposed two-stage process utilizes the same setup parameters (part dimensions, tool diameter, stepdown, feedrate, etc.) used in previous studies. CATIA V5 is the software used to generate the forming tool trajectories for the NC machine-tool. The optimal forming strategy is validated by finite element analyses (FEA) with ABAQUS commercial software. The optimization procedure requires testing several tool paths and analysing the resulting strain states along the flange. The complete calculation process has been automated through several scripts, as discussed below.

3.1. Geometrical parameters and tool path generation

Fig. 3 shows the CATIA models and a schema of the sheet section for the undeformed, intermediate and final parts of the proposed two-stage forming process. As can be seen, in the first stage, a conical surface is proposed for the intermediate zone of the sheet and two cylindrical surfaces are used at the beginning and the end of the stage. The second stage consists simply in generating a cylindrical surface along the whole length of the preformed piece. Thus, the first tool trajectory can be characterized by 3 parameters (see Fig. 3(b)): a height H for the first cylindrical helical path, a slope A for the intermediate conical helical path, and a gap W between the final cylindrical helical path and the first one. The stepdown is 0.2 mm/rev. The section profile of the deformed sheet is obtained by compensating the tool geometry of radius R, represented as a circumference in Fig. 3.

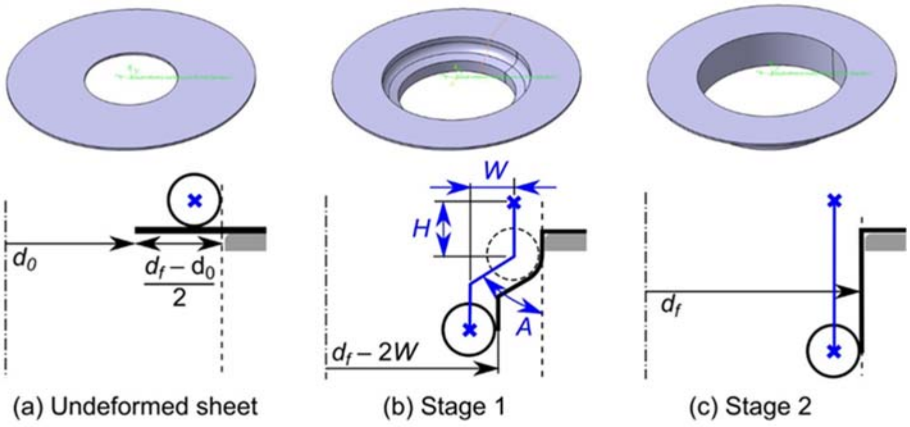

Fig. 3. Geometrical parameters for the SPIF process in two stages.

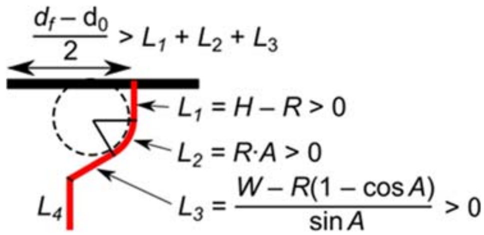

Fig. 4. Dimensional constraints for the intermediate sheet (stage 1).

The CAD model of the sheet geometry is used to calculate the tool trajectories in both forming stages using the CATIA machining workbenches. Dimensional constraints have been established for parameters *A*, *H* and *W* to avoid inconsistent situations in the generation of tool paths. The constraints are obtained by establishing some relationships of the flange length in undeformed and deformed configurations (see Fig. 4) that ensure the integrity of the proposed shape for the intermediate deformed sheet. A minimum angle A of 30° has been established. The valid ranges for parameters are as follows:

$$\begin{aligned} &30^{\circ} < A < 90^{\circ} \\ &R < H < \frac{d_f - d_0}{2} - R \cdot A + R \\ &R(1-\cos A) < W < R(1-\cos A) + \left(\frac{d_f - d_0}{2} - R \cdot A + R - H\right)\sin A \end{aligned} \quad (1)$$

Based on previous experimental studies [7,8], the geometrical dimensions of a successful test in a single-stage process has been used to analyse the proposed two-stage approach. The selected test was carried out using a 6-mm tool radius (*R*) to deform a metal sheet of thickness 1.6 mm and initial hole diameter d_0 = 64.5 mm to a final hole diameter d_f = 95.8 mm. For this configuration, a series of 15 sets of consistent parameter values of *A*, *H* and *W*, varying within *A* = 30–80°, *H* = 7–16 mm and *W* = 1–10 mm, has been selected. A series of macros using the CATScript programming language has been developed to automate the calculation process of forming tool paths in CATIA:

- update_geometry.CATScript: it takes a combination of values of *A*, *H*, *W* and updates the intermediate part geometry of the CAD model (.CATPart file).

- update_toopaths.CATScript: it updates the CATIA process model (.CATProcess file) which includes the tool paths calculation, according to the sheet geometry in the CAD model.
- generate_aptsource.CATScript: it creates a text file (.aptsource) with NC program in APT code for the first stage of the forming process. A program for the second stage is also generated, which is the same for all case studies.

The programs in APT code generated by the scripts aim to simulate the movements of the forming tool in the FE model, as described below. Note that they could also be postprocessed to G-code to perform experimental tests in a CNC machining centre.

3.2. Numerical simulation and analysis

The FE model is carried out in ABAQUS. The material used in the study is aluminium alloy 7075-O sheet of 1.6 mm thickness. A Hollomon type law has been used to characterise the hardening of the material. The mechanical properties of the sheet-metal are summarized in Table 1.

Table 1. Mechanical properties for AA7075-O sheets.

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

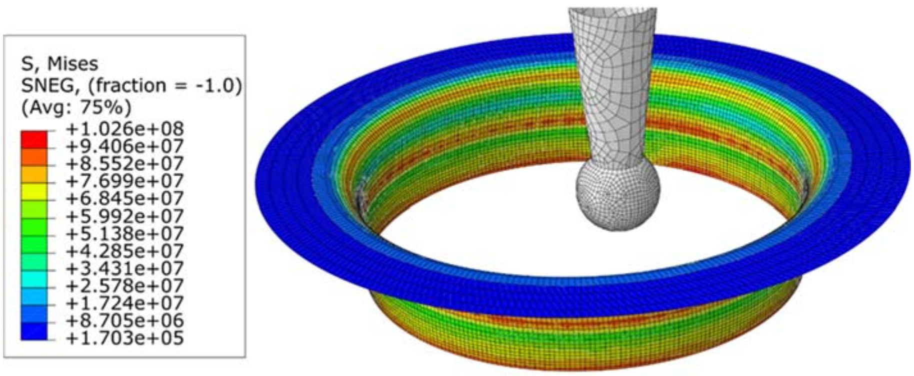

Fig. 5. ABAQUS simulation for hole-flanging by SPIF in a single stage.

The FE model for the sheet was discretised by 2D shell elements by using 360 elements around the circumference, with an approximately size of 1 mm at the edge. A friction coefficient of 0.1 was used. Fig. 5 shows the FEA results for the hole-flanging process by SPIF in a single-stage. The experimental results on previous studies [7,8] have been used to calibrate the FE model. The main drawback of the developed FE models is their computational time, sometimes exceeding one month in a 64-bit PC computer with Intel Core i7 processor and 32 GB of RAM memory.

A series of Python scripts have been developed to automate the analysis of the different sets of parameters *A*, *H* and *W*. These are:

- extract_toolpath_fromAPT.py: it reads the text files with the NC programs in APT code, retrieves the coordinates X, Y, Z and calculates the time of every tool movement. For each program, it generates three text files with the pairs of values time-X, time-Y and time-Z.
- launch_fea_jobs.py: it builds the FE model in ABAQUS for the two-stage process by SPIF, attaches the corresponding files with the tool paths and launches the job for the calculation of the model variables. This script has been developed by modelling the forming process using the ABAQUS graphical interface and debugging the code of the “journal” file (.jnl).

- extract_fea_data.py: it retrieves data from the ABAQUS results file (.odb). Data includes the displacements and strains of nodes along a flange section.
- calculate_thickness.py: it calculates the thickness distribution along the flange. A graphical representation is generated and saved as an image file.

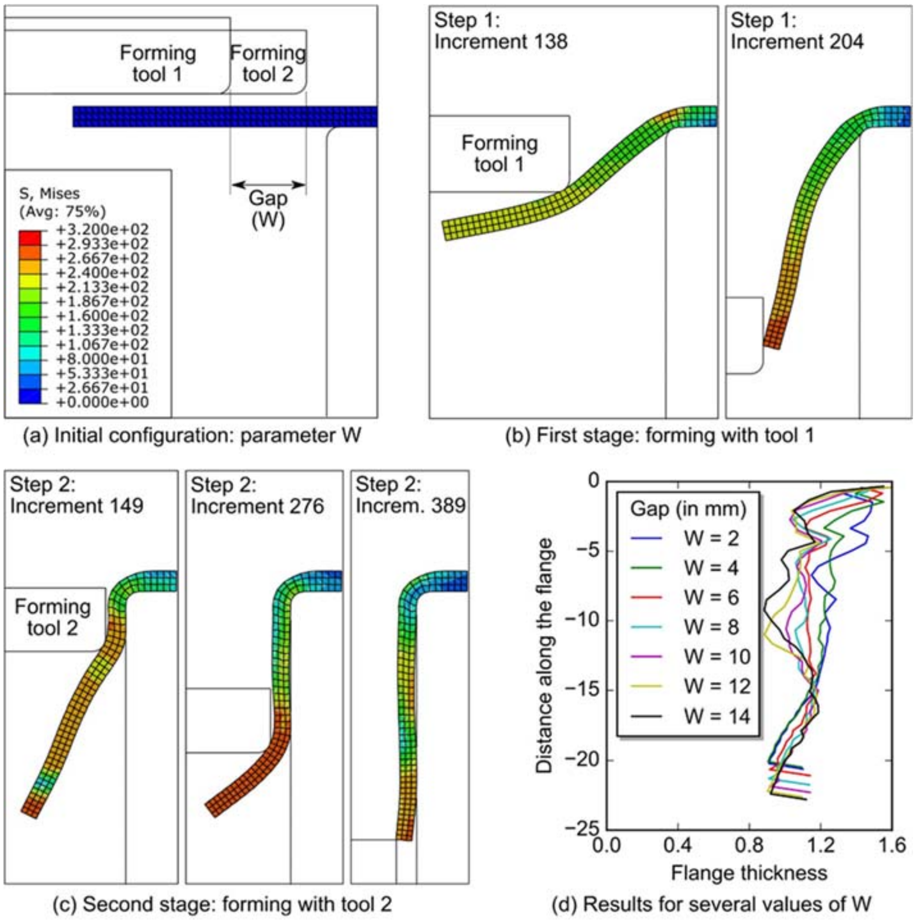

Fig. 6. Parametrized simple model in ABAQUS for hole-flanging by press-working.

As mentioned before, due to the high computational cost of the FE analysis in SPIF, the code of the scripts was debugged using a 2D axilsymmetric hole-flanging process in two stages. Although this simulation is closer to conventional press working than to a SPIF process, it may help to gain insight in the influence of the process parameters at the moment.

The sheet was discretised with a mesh of 0.4 mm size, as illustrated in Fig. 6(a-c). Two different forming tools were used. The tool with smaller diameter is used in the first stage (see Fig. 6(b)), and the larger tool is used for finishing the flange (see Fig. 6(c)). Given the axial symmetry of this simplified model, the forming tools follow linear downward trajectories. Thus, the only parameter to be controlled is the gap between forming tools, *W*. Both forming tools are flat with a rounded edge of 1-mm radius. This edge radius, along with a high value of friction coefficient (0.3), was selected to produce an appreciable variation in sheet thickness. Fig. 6(d) depicts the flange thickness profile obtained with *W* values ranging from 2 to 14 mm. Results reveal that the higher the gap *W* the higher the thickness reduction.

4. Conclusions

This work presents a preliminary study on the optimization of sheet thickness in a hole-flanging process by SPIF in two stages. Based on previous experimental works, a customized intermediate geometry of metal sheet between both stages has been proposed and parameterised. A simple optimization procedure is used to automate the intermediate part design, the generation of the tool tip trajectories and the validation of the optimal forming strategy by means of FEA. The main conclusions of this study can be summarised as follows:

- The optimization procedure is based on interoperability between a CAD/CAM software that generates NC code and a FEA software that utilizes the processed NC code to simulate the tip tool movement.
- The optimization procedure is automated by means of macros or scripts in different programming languages easy to learn and use.
- An early analysis of the intermediate part geometry allows stablishing dimensional constraints in order to avoid an inconsistent geometry in the CAD model.
- A simplified FE model has been used to debug the script code in order to avoid errors in forming process modelling and analysis of results.
- The simplified FE model allows to validate the proposed optimization procedure. The model analyses a conventional hole-flanging process by press-working in two stages with two forming tools of different size. Results show that the higher the difference in size between both tools the higher the thickness reduction of the final flange.
- 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 main drawback of the developed FE model for the SPIF process is its high computational time. Currently the calculation process in SPIF is still in progress and the optimum geometry is not yet known. Nevertheless, it can be anticipated that a better homogenization of the thickness distribution along the flange will be successfully achieved in comparison with a single-stage process. Results will be presented in a future publication.

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