On the effect of stress state on the failure limits of hole-flanged parts formed by SPIF

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Abstract. Single Point Incremental Forming (SPIF) is a novel and flexible forming technology that has been used in the last few years to obtain a variety of customized sheet parts. One of the most valuable advantages of this process is its ability to suppress the localized necking of the sheet, allowing a stable plastic deformation up to the ductile fracture of the sheet. Traditionally the fracture in sheet metal forming is characterized by the conventional Fracture Forming Limit (FFL) curve, obtained with Nakazima or Marziniak tests. However, in many cases the SPIF processes exhibit fracture strains clearly above the conventional FFL, showing an unexpected gain of formability. It is well known that ductile fracture in metals is highly affected by the stress state in the material. Therefore, among others, this fact could contribute to explain the experimental differences observed in the FFL obtained by conventional and incremental operations. The present work develops a numerical model in ANSYS to study the mechanics of the fracture process during the incremental deformation operation. The simulations focus on the hole-flanging operation by SPIF in AA7075-O metal sheets of 1.6mm thickness, recently experimentally analysed by the authors. Different configurations of pre-cut hole diameters are simulated. The evolution of the strain paths and the hydrostatic stress in the SPIF process are analysed and discussed. These variables help to explain the apparent enhancement of formability observed in SPIF processes beyond the conventional FFL curve.

1. Introduction

Single Point Incremental Forming (SPIF) is a novel and flexible technology for small production batches that has been used to obtain a variety of industrial parts. In SPIF, a clamped metal sheet is progressively deformed by a forming tool driven by a CNC machine that follows a pre-established path. Perhaps, the main feature that defines this process is the remarkable enhancement of formability in comparison with conventional sheet metal forming processes. In this technology, the deformation process generates local conditions that delay or suppress the localized necking of the sheet. Thus, the Fracture Forming Limit (FFL) becomes now the limiting process curve instead of the Forming Limit Curve at necking (FLC), being the safe forming region enlarged notably. FFL curve is commonly considered a material property, unlike the necking limits (FLC) which strongly depend on the loading history and non-linear strain paths [1,2]. Figure 1 depicts these limiting curves and the safe regions both in conventional and incremental processes for metal sheets of AISI 304 with 0.8mm thickness [3]. The main factors that contribute to postpone the sheet failure in SPIF are the local and incremental deformation, the localized bending due to the punch radius, the hydrostatic stress and the cyclic straining due to the successive passes of the tool [3,4].
Additionally, in many cases the SPIF processes exhibit fracture strains clearly above the conventional FFL (see Figure 1 right) [3,5]. It is well known that ductile fracture in metals is highly affected by the stress state in the material. Thus, a possible reason for these results could be related to the hydrostatic stress attained in SPIF in comparison with those in conventional sheet metal forming processes. In fact, classical ductile failure criteria include explicitly the hydrostatic stress in their formulations, such as Rice and Tracey [6], Oyane et al. [7], etc. Therefore, hydrostatic stress could explain the experimental differences observed in the fracture limits obtained by conventional and incremental operations. Since this variable cannot be experimentally evaluated, it is necessary to develop numerical models to obtain them in SPIF processes in order to understand the mechanics of the failure process and the parameters that influence this enhancement in formability.

In particular, this paper focuses on circular hole-flanging operations by SPIF using a single-stage strategy [8]. This version of the process, recently published by the authors, allows reducing production times, overcoming the main drawback of SPIF technology. In this process, a fixed sheet with a pre-cut hole ($d_0$) is plastically deformed by a hemispherical forming tool that, following a pre-established path, produces a smooth round flange in a single stage (see Figure 2 left). There are many industrial applications of this process such as strengthening the edge of a hole or providing a region for joining sheet parts to tubes.

The main goal of the present work is to develop a calibrated numerical model of the hole-flanging by single-stage incremental forming and to analyse the sheet failure and the evolution of hydrostatic stress as possible parameter that could explain the apparent enhancement of formability observed in SPIF processes beyond the conventional FFL curve.
2. Experimental procedure

The material used in this study was an aluminium alloy 7075-O, supplied as a sheet of 1.6mm thickness. Several hole-flanging operations by single stage incremental forming were performed in a 3-axis milling CNC machine using a $\phi 12$mm hemispherical forming tool. The specimens were sheet blanks with different initial pre-cut hole diameters ($d_0$). Samples were electro-etched with a dot pattern in order to compute principal strains using an optical 3D forming analysis system (ARGUS®). The step down was set to 0.2 mm/turn, the theoretical inner hole diameter was always $d=95.8$mm and the forming trajectories were developed using CATIA V5 (see Figure 2). Further details about the experimental campaign and the results can be found in [8].

In this work we will focus on the pre-cut hole diameters at the formability limit, i.e. the smallest diameter that allow obtaining a successful flange and the greatest diameter that produces a failed flange. For the material here analysed and the selected test parameters, the pair of tests with a $\phi 63.5$mm and $\phi 65$mm pre-cut holes corresponds to a failed and successful hole-flanged parts, respectively (see Figure 3).

3. Numerical simulation

The numerical simulation of the single-stage hole-flanging tests by SPIF was performed using the explicit solver of ANSYS. The full specimen was modelled since there was no symmetry conditions due to the nature of the loads. The mesh was constructed using shell elements with 4 nodes and 12 degrees of freedom were used. Five integration points across the sheet thickness were arranged. Figure 4 (left) depicts the virtual setup and the finite element mesh. As it can be seen, the role of the blankholder was modelled with a clamped boundary condition in that region. A numerical simulation of the process and the thickness strain contour in a failed flanged part is shown in Figure 4 (right).

The forming tool and backing plate were assumed to be rigid bodies. The yielding behaviour of the sheet followed the Barlat and Lian anisotropic criterion [9]. The coefficients describing the anisotropic behaviour were calculated from the experimentally measured r-values and the elastic properties were supposed to be isotropic, according to experimental results [8,10]. The plastic behaviour was fitted using a Hollomon-type hardening law as follows:

$$\sigma(MPa) = 255 \varepsilon_p^{0.06}$$  \hspace{1cm} (1)

A Coulomb’s friction law was selected, considering friction factors $\mu=0.15$ both in tool-metal sheet and backing plate-metal sheet contacts. Further details about the numerical model can be found in [11].
4. Results and discussion

Several simulations of single-stage hole-flanging operations by SPIF were carried out using several sizes of the pre-cut hole diameters. The numerical predictions of the failure or success for each simulation were analysed according to the evolution of the strain paths within the experimental Forming Limit Diagram. Thus, failure was detected when any point of the specimen reached the FFL, which represents the experimental onset of fracture in the sheet.

According to this criterion, the predicted sizes of the pre-cut hole diameters at the formability limit were φ67.5 mm and φ68 mm, corresponding to a failed and a successful flanged parts, respectively. Although there is a slight deviation, these values agree reasonably well with experimental data. Thus, the comparison of numerical and experimental pairs of successful and failed specimens at the formability limit will be carried out from a qualitative point of view. In any case, further works will be performed in a future to refine and calibrate accurately the numerical model with experimental results. Figure 5 shows the numerical contour of Z-displacement and final geometry of the failed and successful flanged part for a pre-cut hole of φ67.5 mm and φ68 mm, respectively.

![Figure 5](image)

**Figure 5.** Z-displacement (m) for a failed (left) and successful (right) flanged part of φ67.5 mm and φ68 mm pre-cut hole, respectively.

![Figure 6](image)

**Figure 6.** Experimental (black dotted line) and numerical (blue line) strain distribution in a section along the flange in a failed flange (left). Numerical strain evolution (dashed lines) of points a, b, c along the process (right).

As can be seen, the total height of the flange in the successful case is around 18 mm. This value allows obtaining the average axial stretching sustained by the flange. The numerical model predicted a flange elongation of 32% whereas experimental specimens undergone a value around 43%. These results are in reasonably agreement.

Figure 6 depicts the experimental and numerical major and minor principal strains along a straight section in the flange (see Fig. 5 left). Blue line represents the numerical simulation of φ67.5 mm pre-cut hole specimen and black dotted line the experimental results measured using ARGUS® for a sample with a φ63.5 mm pre-cut hole. It is also depicted the FFL curve, which was obtained by using conventional sheet metal tests (Nakazima test) at different strain paths in a previous work [8]. Both
cases, numerical and experimental, correspond to the greatest diameter that produces a failed flanged part, i.e. at the formability limit. It can be seen that the region at the middle of the flange (point B in Figure 5 and 6) is the most strained of the sample, reaching the FFL, and being the place where the fracture took place. As can be seen, the shape of numerical and experimental curves matches reasonably well. In addition, one of the most interesting capabilities of numerical model is the possibility of analysing the temporal evolution of the variables. Particularly, Figure 6 (right) shows the temporal evolution of 3 points along the flange (points a,b,c) within the FLD. As expected, the strain state of the point c, near the edge of the pre-cut hole, evolved globally close to pure tension state ($\beta = -0.5$) during the whole process. Point a, at the top of the flange, and point b, located at the middle region, exhibited global strain states in the biaxial region.

It should be noted that Figure 6 (left) also depicts the experimental fracture strains at the crack site (point B) measured directly on the crack lips. This value is shown by a black open mark. As can be seen, fracture strains exhibited for this material are clearly above the conventional FFL. In fact, they are even outside the wide scatter bands of the conventional fracture limits. As it was mentioned, hydrostatic stress could be an important factor to increase apparent formability in SPIF. It is well known that a negative hydrostatic stress prevents voids growth, delaying the fracture occurrence.

**Figure 7.** Numerical evolution of hydrostatic stress, at the outer and inner surfaces, around the middle of the flange in a failed specimen with $\phi 67.5$mm pre-cut hole.

Figure 7 depicts the temporal evolution of the hydrostatic stress ($\sigma_h = (\sigma_1 + \sigma_2 + \sigma_3)/3$) versus the Z-tool displacement, at the inner surface (in contact with the tool) and at the outer surface in a point located around the middle of the flange, i.e. the region where the material undergoes a more severe stretching and thinning, for the failed flanged part at the formability limit ($\phi 67.5$mm pre-cut hole). The curves are shown up to the predicted fracture occurrence. The peaks in the stress evolution are due to the successive passes of the tool at the point analysed here.

It can be seen that, as expected, the hydrostatic stress is smaller at the inner surface than at the outer side, due to the punch-sheet contact pressure. This fact reveals that according to the classical fracture criteria, the greater the hydrostatic stress the higher accumulated damage. So, the final failure is controlled by the outer surface of the specimen. Furthermore, it can be observed that during the last stages of the process before fracture, the average level of hydrostatic stress at the outer surface is very low or even negative. This fact could be the responsible of promoting a certain enhancement on formability in SPIF processes compared to conventional ones.

In this regard, it is well established that for a conventional process under proportional loading, the stress triaxiality ($\sigma_h/\sigma$) depends on the local strain ratio $\beta$ and the anisotropy coefficient ($r$) [5].
Assuming for simplicity an isotropic material (Mises plasticity) the stress triaxiality takes a value around 0.577 for plane strain and 0.66 for an equibiaxial state. Therefore, a theoretical conventional test performed in the first quadrant of the FLD, as the SPIF process here analyzed (see Figure 6), should have a stress triaxiality between 0.577 and 0.66. Due to the hardening curve assumed for this material (Equation 1), the equivalent stress ($\sigma_e$) becomes almost constant for equivalent strains higher than 0.4, taking a value around 255MPa. Therefore, the value of the hydrostatic stress ($\sigma_H$) in a theoretical conventional test of this material under plane strain conditions at high strain level would be around 147 MPa and 170MPa for an equibiaxial strain state. These levels of hydrostatic stress in a theoretical conventional test are also shown as dashed blue lines in Figure 7.

It can be concluded that the ISF process is able to evolve with average hydrostatic stress levels substantially smaller than in conventional sheet processes for a similar global strain ratio $\beta$ during the process. This fact seems to be a possible reason for reaching fracture strains in SPIF above the conventional FFL in some materials and in particular the AA7075-O analysed here. As previously discussed, it is understandable that two processes with different levels of hydrostatic stress do not have the same fracture strains in terms of classical fracture criteria mainly depending on this variable.

5. Conclusions
The present work developed a calibrated numerical model in order to better understand the mechanics of the failure process and the parameters that influence the enhancement in formability observed during incremental deformation operations. The simulations were focused on hole-flanging processes by SPIF using a $\phi$12 mm hemispherical forming tool. The main conclusions of this work can be summarized as follows:

- The numerical results of the smallest pre-cut hole diameter that allow obtaining a successful flanged part and the greatest diameter that produces a failed flange agree reasonably well with the experimentally performed.
- The numerical evolutions of the principal strain paths in a section along the flange for failed and successful flanged parts were satisfactorily compared with experimental data.
- It has been pointed out that hydrostatic stress numerically evaluated during the SPIF process was substantially smaller than those in conventional sheet forming operations. This variable help to explain the apparent enhancement of formability observed in SPIF processes beyond the conventional FFL curve. Therefore, this variable should be taken into account for predicting failure by fracture when incremental operations are analysed.

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