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Fracture in hole-flanging produced by single point incremental forming

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ABSTRACT

Hole flanging produced by single point incremental forming is a new manufacturing process in which a sheet, with a concentric pre-cut hole and the outer periphery rigidly fixed by a blank holder, is progressively forced with a tool to produce cylindrical or conical smooth flanges. The formability limits of the process are known to be higher than those commonly found in hole-flanging produced by conventional press-working due to suppression of necking with a low growth rate of accumulated strains above the forming limit curve.

The aim and objectives of the paper is to evaluate the critical values of fracture toughness and ductile damage at crack initiation according to different damage laws and to correlate these values with independently determined values of the forming limits at fracture. The presentation starts by tracing the strains and stresses of various positions over the surface of the hole-flanged parts at different intermediate stages of deformation. It is revealed that the strain loading ratios are constant for different material elements. From these data, the experimental values of accumulated damage at various positions are determined, particularly at the site of fracture.

1. Introduction

Single Point Incremental Forming (SPIF) is a dieless manufacturing process that progressively shapes a blank (clamped rigidly around its edges, but unsupported underneath) by means of a simple hemispherical-ended forming tool that may be free or rotating and which describes the contour of the desired geometry. Fig. 1 presents the basic components of the process: (a) the sheet metal blank, (b) the rig with the backing plate, (c) the pressure pad, and (d) the rotating single-point forming tool.

In the early years of development of SPIF most studies concerned experimental investigations on the capability and flexibility of the process to produce prototypes and small batches of sheet metal parts (Fig. 1a) in which the path of the rotating tool was driven by either ordinary computer numerical control machine tools or special purpose machine tools. Only a limited number of studies on the characterization of the formability limits of the process in terms of the major operative variables have been carried out in this period. The keynote paper by Jeswiet et al. [1] provides a comprehensive review of the research on SPIF that was performed between the end of 1990s and 2005.

The understanding of the deformation mechanics of SPIF and of the physics behind failure just came recently by means of finite element studies [2,3], analytical developments [4,5], experimental measurements and observations [6,7]. Typical modes of deformation were identified, different mechanisms to explain plastic deformation above the forming limit curve (FLC) were proposed and the formability limits of the process were established across the useful range of process conditions. The state-of-the-art review paper by Emmens and van den Boogaard [8] presents an overview of the most significant contributions in the field with special emphasis on the mechanisms that were proposed to explain plastic deformation above the FLC.

The focus on the above mentioned mechanisms was due to experimental observation that failure in SPIF occurred by thinning without evidence of localized necking taking place before reaching the onset of fracture. The first explanation of plastic flow above the FLC in the light of modern ductile fracture mechanics was proposed by Silva et al. [4] who employed a ductile damage criterion based on the triaxiality ratio $\sigma_m/\overline{\sigma}$ between the hydrostatic stress σ_m and the effective (flow) stress $\overline{\sigma}$ to determine the slope of the fracture forming line (FFL) in the principal strain space. The prediction of the formability limits of SPIF by means of

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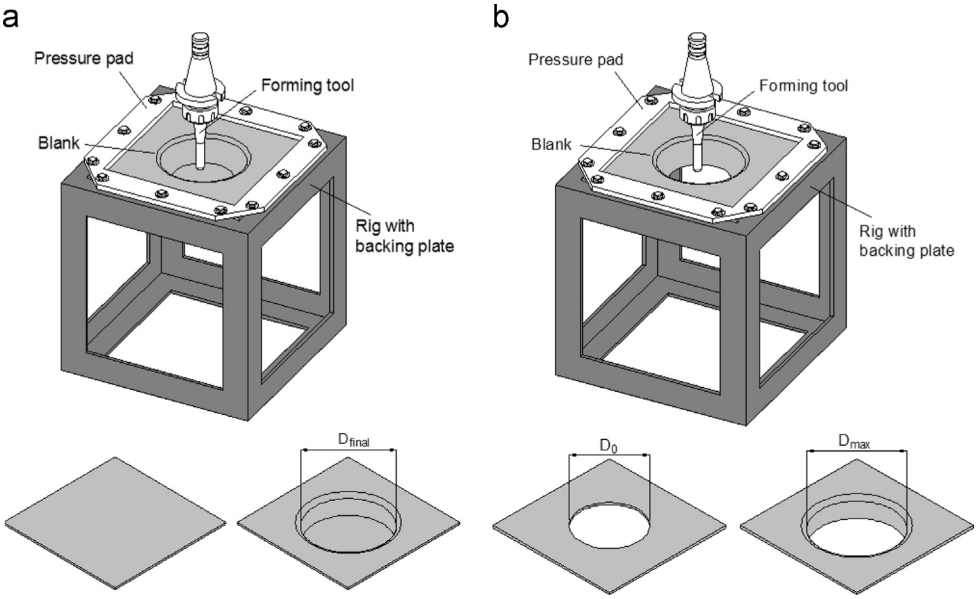

Fig. 1. Schematic representation of the fabrication of (a) sheet metal parts and (b) flanges in sheet metal blanks with pre-cut holes by means of SPIF.

ductile damage criteria was further investigated by other researchers. Cao et al. [5], for example, combined the Oyane ductile fracture criterion [9] with an analytical model to quantitatively understand the effects of tooling and process parameters related to sheet thickness. Huang et al. [10] produced finite element estimates of the onset of fracture in a conical cup by means of the Oyane ductile fracture criterion. Malhotra et al. [11] made use of the plasticity damage model due to Xue [12] and performed finite element analysis of a cone and a funnel with a plasticity damage criterion to demonstrate that the local nature of deformation in SPIF and suppression of necking is primarily responsible for the increased formability, in spite of greater damage accumulation as compared to conventional press-working.

The abovementioned methodologies to correlate ductile damage and plastic flow above the FLC made use of different procedures to determine the critical values of damage. Silva et al. [4], for example, measured the strains of a SPIF benchmark sheet metal part at the onset of failure to set up critical damage and the position of the FFL in the principal strain space. Cao et al. [5] measured the strains at the onset of failure in two different types of tensile tests to determine the material constants of the Oyane ductile damage criterion. Huang et al. [10] utilized a similar procedure to that of Cao et al. [5] with data retrieved from bi-axial tensile tests available in the literature. Malhotra et al. [11] performed a manual adjustment of the different constants of Xue's ductile damage material model by matching the forming tool *z*-forces obtained from finite element simulation with those measured during the experiments.

None of the above mentioned publications presents a simple, effective and independent methodology to determine the critical values of damage at crack initiation directly from the experimental values of strains and stresses at various positions over the spiffed workpieces. Moreover, nobody has ever considered the possibility of determining fracture toughness of sheet metal products by means of SPIF.

In fact, the successful determination of the critical values of damage and fracture toughness at crack initiation are among the most relevant experimental data to be supplied to finite element computer programs that are commonly utilized to simulate sheet metal forming and single point incremental forming, in particular.

Under these circumstances, the aim and objective of this paper is to combine circle-grid analysis due to Keeler [13] and Goodwin [14] and failure map concepts due to Glover et al. [15] to trace strains and stresses along the deformation history of material and determine the experimental values of critical damage and fracture toughness. Experiments in hole-flanging produced by SPIF (Fig. 1b) give support to the presentation.

The organization of the paper is the following. Section 2 summarizes the procedures utilized in mechanical and formability characterization of the material, presents the essentials of the new proposed methodology to determine the critical values of damage and fracture toughness, and describes the work plan utilized in background hole-flanging experiments. Section 3 presents and discusses the results, analyzing plastic flow above the FLC in the light of the FFL, ductile damage and fracture toughness. Section 4 presents the conclusions.

2. Material and methods

2.1. Mechanical and formability characterization

The research work was carried out on aluminum AA1050-H111 sheets with 1 mm thickness. The specimens utilized in the mechanical and formability characterization of the material were cut out from the supplied sheets at 0°, 45° and 90° degrees with respect to the rolling direction.

The mechanical characterization of the material was performed by means of tensile tests in an Instron 4507 testing machine and the average stress–strain curve was approximated by the following Ludwik–Hollomon's equation:

$$\sigma = 140\varepsilon^{0.04} \text{ (MPa)} \tag{1}$$

The values obtained for the modulus of elasticity E, the yield strength σ_Y, the ultimate tensile strength σ_{UTS}, the anisotropy coefficient r and the elongation at break A at 0°, 45° and 90° degrees with respect to the rolling direction are provided in Table 1. The average value of the anisotropy coefficient $\bar{r}$ is obtained from,

$$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{2}$$

The formability limits at necking (FLC) and fracture (FFL) were characterized by means of laboratory formability tests that cover strain paths from uniaxial to plane-strain and biaxial loading conditions. The technique utilized for measuring the in-plane