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An experimental study on some formability evaluation methods in negative incremental forming

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Abstract

In single point incremental forming (SPIF), the final thickness of a deformed sheet can be predicted by the sine law. Therefore, the formability in SPIF can be expressed as the *maximum wall angle* (θ_{max}) that a sheet would endure without fracturing. In the present study, two tests were carried out in order to evaluate the formability of an aluminum sheet. In the first test, conical frustums and square pyramids, a set of each, were produced by systematically varying the wall angle in order to investigate θ_{max}. In the second test, four conical frustums, each having varying wall angle, designed by revolving different curved lines were formed to fracture. The results revealed that the value of θ_{max} obtained from the former test was smaller than those obtained from the latter one. Moreover, a variation among the values of θ_{max} obtained from the parts of the second test was also found. Since the first test shows the minimum possible value of θ_{max}, it should be employed in combination with the second test so as to minimize the number of experiments required.

Keywords: Negative incremental forming; Formability tests; Maximum wall angle; Sine law

1. Introduction

In the recently past years, many sheet-metal-forming techniques have been under study in order to develop novel forming processes, such as laser forming, water assisted forming and single point incremental forming (SPIF), characterized by high flexibility. These techniques are characterized by the possibility of being easily adopted to produce small production batches using low cost tooling. Among these innovative processes [1–7], SPIF has attained a great attention.

In the simplest form of the SPIF process, the final component shape is determined by the relative movement of a tool with respect to the blank rather than the die shape. The process is usually carried out on CNC machines where it is possible to assign and control the tool motion according to the fixed paths [4–7]. The process has two variants: negative incremental forming and positive incremental forming [8] (Fig. 1). In the former variant, the blank is backed with a die that increases the probability to produce parts with sharp corners in contrast with the latter one.

Like other sheet-metal-forming processes, SPIF also suffers of some forming defects for instance spring back and bending close to the clamped zone [9]. However, these defects can be minimized by optimizing the process parameters. The production rate of the novel process is not as high as those of existing ones. Nevertheless, some other outstanding features, such as flexibility and low cost tooling, make it feasible to manufacture parts in small batches for various applications [10–13], which are listed below:

- It is a very economical process for rapid prototyping;
- The method creates large regions of homogenous deformation and avoids the large stress and strain gradients. Due to this fact, a specimen formed by the process is considered to be more reliable to calibrate a void nucleation model than the tensile specimens;
- Finally, it is capable to manufacture a variety of irregular-shaped components and highly customized medical products.

In short, due to the inherent advantages and flexibility, the process offers the possibility to implement a powerful alternative.

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Nomenclature

Terms

Generatrix a curve whose motion generates a surface or a solid

Revolved surface a surface generated by the motion of generatrix

Transition point a point, which is located closest to fracture, on which the theoretical and experimental values of thickness of a part are found to be in accordance

Relations

$t = t_0 \sin\alpha = t_0 \cos\theta$ the sine law

Notations

a, b, e, k constants used in the equation of circle, ellipse, parabola and exponential function

$C(x_c,y_c)$ transition point (Fig. 4d) on a part, whose wall angle varies

$D(x_d,y_d)$ fracture point (Fig. 4d) on a part whose wall angle varies

h_p the depth of a part measured to an arbitrary point $P(x,y)$

$P(x,y)$ an arbitrary point on a surface (Fig. 4b)

$P_1(x_1,y_1)$, $P_2(x_2,y_2)$ the initial and end points of a generatrix or a surface (Fig. 4b)

R radius of a circular arc

t thickness of a formed part

t_0 thickness of a blank

Greek symbols

α half-apex angle of a part

θ wall/slope angle of a part

θ_p wall or slope angle on an arbitrary point on a part

θ_1,θ_2 the wall/slope angles on the initial and end points of a part or a generatrix, respectively

Several studies have been performed with emphasis on assessing the formability in this forming method [14–17]. There are two ways to express formability: an FLC that presents the limiting strains [14,15], and θ_{max} that is the maximum wall angle (θ_{max}) without fracture of the sheet metal [16,17]. In the current work, formability has been expressed as θ_{max}. Young [16] produced a collection of conical samples with a variety of wall angles in order to investigate θ_{max} for an aluminum sheet. In order to avoid forming of a large number of samples required, as reported in [16], a new formability test was devised in the previous work [17]. In this test, a conical surface, which was designed by revolving a circular arc, having varying wall angle was formed to fracture. In the present investigations, both the tests [16,17] were employed to test the formability of an aluminum sheet. However, the variety of shapes formed in the previously devised test (see [17] for detail) was increased from one to four in order to study the effect of the specimen shape on formability. For this purpose, conical frustums each with varying wall angle were modeled by revolving various curves, which were the segments of circular, parabolic, elliptical and exponential curves, and formed to facture by negative incremental forming. The results were quantitatively analyzed within – and between – the specimens of the tests. Based on the analysis, some conclusions have been drawn, and a methodology to determine the minimum possible value of the formability parameter 'θ_{max}' has been proposed.

2. The experimental set-up and the process parameters

The material used in the current study was an aluminum sheet with 0.91 mm thickness. Tensile tests were performed in order to determine the mechanical properties of the sheet, given as follows: elastic modulus = 72 GPa, yield strength = 94 MPa, ultimate tensile strength = 177 MPa, elongation = 21%, and modulus of rigidity = 27 GPa.

The commercial CAD/CAM software 'UG NX-3' was utilized for designing and tool path generation. The spiral tool path [4–7] was used to control the tool motion. The blank having the size of (140 mm × 140 mm) was held at the periphery by a blank holder as presented in Fig. 2, and a CNC milling machine tool was employed to deform the blank. A HSS tool with the hemispherical end of 8 mm diameter shaped the part at the room temperature. The forming tool traveled along the closed-loop path at the horizontal feed rate of 2500 mm/min and the vertical feed of 0.15 mm/revolution. Both the tests were conducted under the same forming conditions.

3. Formability evaluation

The formability of the aluminum sheet was evaluated by employing two methods, which are described as follows.

3.1. Test-1

In SPIF, the final thickness of a part depends on the wall angle (slope angle θ has been referred as wall angle) [16–18]. Therefore, in an attempt to form a new material by SPIF, the initial testing begins with a search for the maximum wall angle that the metal would withstand without fracturing. The maximum wall angle 'θ_{max}' was investigated by producing the collections of conical frustums and truncated square pyramids, a few of which are shown in Fig. 3. The deformation angle was varied in steps, as detailed in Table 1, until 'θ_{max}' was determined. In all of the parts, the base and bottom dimensions were kept constant, which are given as follows: major diameter of frustum = 68 mm, minor diameter of frustum = 30 mm, side length of the base of pyramid = 68 mm, and side length of the bottom of pyramid = 30 mm.

3.2. Test-2

3.2.1. A brief introduction of the test

In the Test-1, a large number of parts have to be produced in order to evaluate the exact formability of a sheet. This laborious and costly testing method can be replaced by a novel one, as