

Deformation Analysis of Incremental Sheet Forming

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ABSTRACT

Incremental Sheet Forming (ISF) is an emerging sheet metal prototyping technology where a part is formed as one or more stylus tools are moving in a pre-determined path and deforming the sheet metal locally while the sheet blank is clamped along its periphery. A deformation analysis of incremental forming process is presented in this paper. The analysis includes the development of an analytical model for strain distributions based on part geometry and tool paths; and numerical simulations of the forming process with LS-DYNA. A skew cone is constructed and used as an example for the study. Analytical and numerical results are compared, and excellent correlations are found. It is demonstrated that the analytical model developed in this paper is reliable and efficient in the prediction of strain distributions for incremental forming process.

INTRODUCTION

Incremental Sheet Forming (ISF) is a manufacturing process for sheet metal prototyping and small volume production where the blank is incrementally deformed into a desired shape by one or more stylus tools traveling along a prescribed path. Conventional ISF can be categorized into two types, Single-Point Incremental Forming (SPIF) where the sheet metal is formed from one side by a single stylus tool; and Double-Point Incremental Forming (DPIF) where a die is positioned underneath a stylus tool pushes the sheet metal to wrap around the die. More recently a Freeform Incremental Forming (FIF) is developed at Ford Motor Company where

two stylus tools synchronized in motion and deform the sheet metal from opposite sides as they are traveling to form a product shape. The new technology provides significant advantages for sheet metal fabrication process in terms of cost and flexibility because forming dies are completely eliminated and complex geometries can be formed. In general small hemispherical stylus tools are used to locally deform the sheet instead of the conventional punch. The sheet metal is clamped along its periphery on a platform to prevent any metal slippage or draw-in. A pre-determined tool path program feeds into a Numerically-Controlled (NC) machine or other robotic arms which controls the movement of stylus tools. Due to the process's flexibility, low-cost and short lead-time, it has been the focus of extensive research over the years. Major research interests included the understanding and development of incremental forming mechanics; failure prediction and formability assessment; and the development of more efficient manufacturing process. Most work focused on experiment techniques and finite element simulations of simpler geometries. Matsubara [1] first established that the cosine law was an accurate prediction of wall thickness in incremental forming. The cosine law can be expressed as:

$$t = t_0 \cos \phi$$

Where t is the wall thickness after forming; t_0 is the initial sheet thickness and ϕ is the so-called forming angle. The forming angle ϕ is defined as the angle between the wall of the formed part and the initial sheet plane. It has been verified

by many researchers on truncated cones, pyramid and other relative simple shapes [2,3,4,5,6,7,8,9].

The objective of this paper is to develop a general mathematical model which is capable of predicting strain distributions for arbitrary geometries and tool paths. The predicted strain distributions can be used to determine a part's formability by comparing the strain values to the ISF Forming Limit criteria [10,11,12]. The model is an extension of the cosine law. Numerical studies are also conducted to validate the analytical model. Comparison with experimental measurements will be presented in a later study. A skew cone is constructed and used as example to illustrate the investigation.

MATHEMATICAL MODEL FOR DEFORMATION ANALYSIS

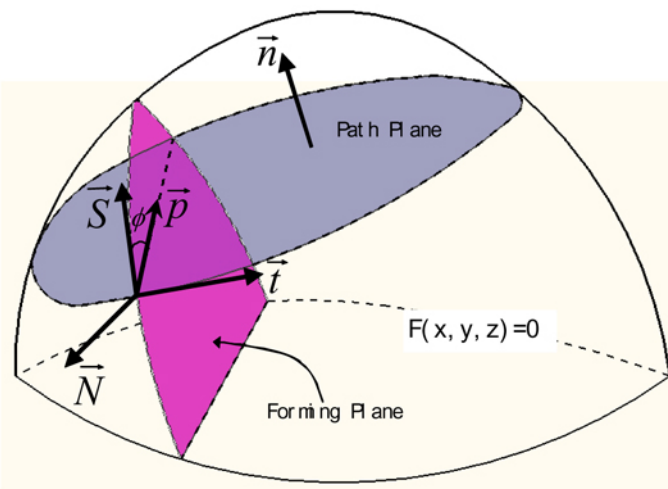


Figure 1. Mathematical Model of Strain Calculate in Incremental Forming

In reference to Fig. 1, let's suppose that the surface geometry of the part to be formed is represented by function $F(x, y, z) = 0$. Consequently the forming surface normal can be expressed as:

$$\vec{N} = \vec{\nabla} F(x, y, z)$$

If $\vec{n}$ is the normal direction of the tool path plane and $\vec{t}$ is tool path direction, the tool path curve normal is $\vec{p} = \vec{n} \times \vec{t}$, and the forming plane's tangential direction should be $\vec{S} = \vec{N} \times \vec{t}$. So the real forming angle ϕ is defined as below:

$$\cos \phi = \vec{S} \cdot \vec{p} = (\vec{N} \times \vec{t}) \cdot (\vec{n} \times \vec{t}) = (\vec{N} \cdot \vec{n}) - (\vec{N} \cdot \vec{t})(\vec{n} \cdot \vec{t}) = \vec{N} \cdot \vec{n} \quad (1)$$

Forming strains are:

$$\varepsilon_{ss} = -\ln(\cos \phi) = -\ln(\vec{N} \cdot \vec{n}) \quad (2)$$

$$\varepsilon_{tt} = 0$$

This mathematical model is rather general in predicting strain distributions. It is applicable not only for the traditional simple part shape but also for any part shape. Eq. (2) establishes that the forming strain depends only on the forming surface normal and path plane normal directions. They can be obtained relatively easily through algebraic and geometric methods.

STRAIN CALCULATION FOR A SKEW CONE

A variety of analytical geometric shapes have been studied by the authors, including simple cones, spherical cones, hyperbolic cones, elliptical cones and skew cones. The study for a skew cone is presented in this paper to demonstrate the process.

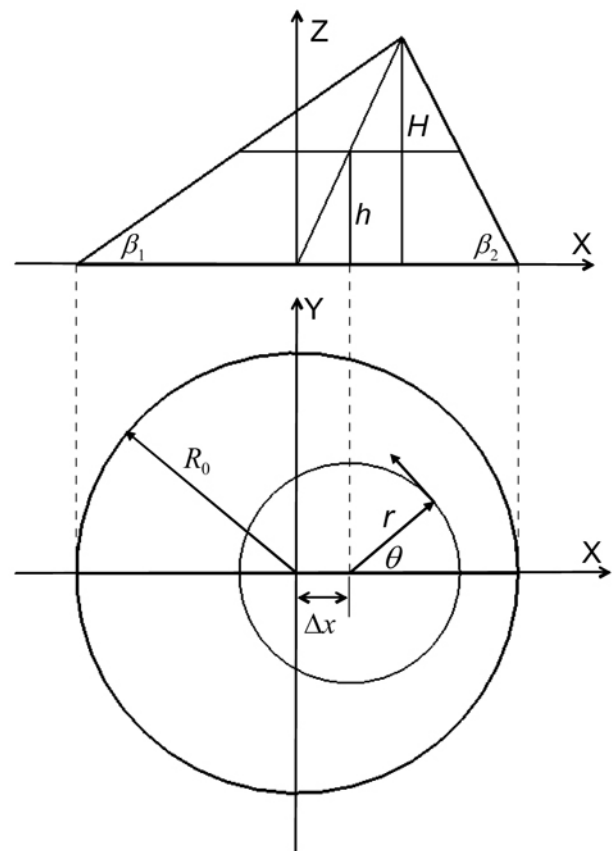


Figure 2. Schematic of A Skew Cone (Side View and Top View)