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Revisiting the fundamentals of single point incremental forming by means of membrane analysis

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Abstract

Knowledge of the physics behind the fracture of material at the transition between the inclined wall and the corner radius of the sheet is of great importance for understanding the fundamentals of single point incremental forming (SPIF). How the material fractures, what is the state of strain and stress in the small localized deformation zone and how these two subjects are brought together in order to explain the overall formability of SPIF in terms of ductile damage are still not well understood. However, they are of great importance for improving the robustness and enhancing the predictability of currently existing numerical models and for extending the scope of industrial applications of the process. This paper attempts to provide answers to these questions by means of a new theoretical model for rotational symmetric SPIF that was developed under membrane analysis with bi-directional in-plane contact friction forces.

Keywords: Single point incremental forming; Fundamentals; Membrane analysis

1. Introduction

Single point incremental forming (SPIF) is a new sheet metal forming process with a high potential economic payoff for rapid prototyping applications and for small quantity production.

Fig. 1 presents the basic components of the process: (i) the sheet metal blank; (ii) the blankholder; (iii) the backing plate; and (iv) the single point forming tool. The tool path is generated in a CNC machining center and is utilized to progressively form the sheet into a component. During the process there is no backup die supporting the back surface of the sheet.

Most investigations of SPIF have concerned applications and formability limits of the process [1]. This observation applies equally to experimental investigations as to the small available amount of finite element studies.

The experimental investigations lead to the conclusion that the formability of the process can be defined in terms of four major parameters: (i) thickness of the sheet; (ii) size of the step down; (iii) speed; and (iv) radius of the forming tool [1]. The influence of the first and second parameters is commonly explained by means of the sine law $t_f = t_0 \sin\lambda$, where t_0 is the initial thickness, t_f is the final thickness, λ is the semi-cone angle and $\psi = \pi/2 - \lambda$ is the drawing angle between the inclined wall surface and the initial flat configuration of the sheet. The speed of the forming tool is known to influence formability because of its direct influence on the frictional conditions at the tool–sheet interface. In what concerns the radius of the forming tool it is experimentally observed that better formability is achieved with the utilization of smaller tools. Smaller tools are claimed to be able to concentrate the strain at the zone of deformation in the sheet under the forming tool, whereas larger tools tend to distribute the strains over a more extended area making the process more similar to conventional stamping.

Despite the major contributions made by Matsubara [2], Iseki and Kumon [3], Jeswiet and Hagan [4], Micari et al. [5], Allwood et al. [6], Bramley et al. [7], Hirt et al. [8], Duflou et al. [9] and many others, on the development of industrial applications and better characterization of the forming limits of the process, the mechanics of deformation

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Nomenclature

σ_θ	circumferential stress
σ_ϕ	meridional stress
σ_t	thickness stress
σ_Y	yield stress
μ	coefficient of friction
λ	half cone angle of the component
ψ	draw angle between the inclined wall and the initial flat configuration of the sheet
t	thickness of the sheet
t_0	initial thickness of the sheet
t_f	final thickness of the sheet
r	radial coordinate
r_2	radius of the element normal where it cuts the z-axis
r_1	radius of curvature of meridian at the element (radius of the SPIF tool)

remains little understood due to the complexity and low predictive ability of the finite element models that, so far, have been employed to study the process. In fact, nowadays, SPIF is one of the very few if not the only sheet metal forming process in which the advantage of experimentation over theory is absolute even for solving the simplest practical problem.

From what was mentioned before it can be concluded that there is a need for a simple but effective theoretical model that allows the influence of major fundamental process parameters and their mutual interaction to be studied both qualitatively and quantitatively.

Such a model must draw from the characterization of the small plastic zone created by the single point forming tool during incremental deformation to the physics behind the onset of cracking at the region where the inclined wall of the sheet is tangent to the corner in contact with the tool. How material separates and cracks propagate along the circumferential direction is still not well understood, although being of great importance for understanding the mechanics of deformation and for improving formability and extending the applicability of the process.

In fact, the incremental nature of SPIF raises important key questions that need to be properly addressed: What is the state of strain and stress at the small plastic zone created by the forming tool? What is the physics behind cracking at the transition between the inclined wall and the corner radius of the sheet being formed? Are the cracks formed by shear or by tensile stresses? Is it possible to explain the formability of SPIF being higher than that of conventional stamping by means of damage based concepts?

This paper attempts to provide answers to these issues by means of a theoretical investigation based on membrane analysis of the small plastic zone created by the single point tool during forming of rotational symmetric components.

2. Membrane analysis of rotational symmetry SPIF components

The governing mode of deformation in SPIF is subject of controversy in the metal forming community [10]. Some authors claim that deformation takes place by stretching instead of shearing while others claim the opposite, but assertions are mainly based on 'similarities' with well-known processes of stamping and shear-spinning rather than on achieved results or experimental evidence.

As it will be shown later in Section 3, examination of the likely mode of material failure at the transition zone between the inclined wall and the corner radius of the sheet

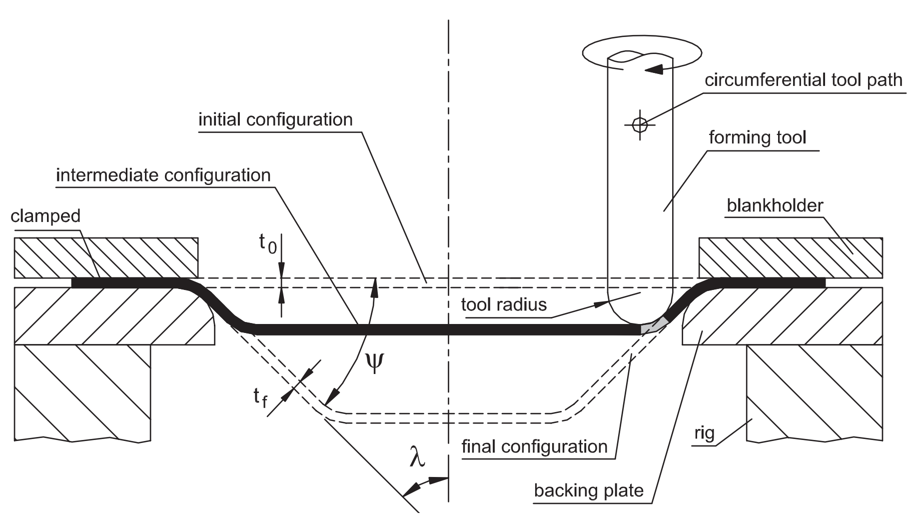

Fig. 1. Schematic representation of a cross section view of the rotational symmetric single point incremental forming (SPIF) process. The tool rotates while performing a round (or helical) path.