TENDENCIES IN FORMING SHEET METAL PARTS USING INCREMENTAL FORMING ADVANCED TECHNOLOGIES

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Abstract: Stretch forming of sheet metal materials is a highly required process in aerospace industry for manufacturing skin parts. Automation of some processes such as cutting, punching, forming, shearing and nesting in conventional manufacturing tends to combine these forming methods. Some researches are made on the formability of sheet metal materials obtained in incremental forming process with stretch forming and water jet incremental micro-forming with supporting dies. This paper is an attempt to review the newly researches made on optimization of manufacturing metal skin parts to achieve geometrical accuracy.

Keywords: stretch forming, water jet, incremental forming, skin parts

1. INTRODUCTION

According to National Science Foundation Industry-University Cooperative Research Centers (NSF I/UCRC), sheet metal forming industry is demanding for advanced processes to produce functional and prototype sheet metal parts and even to repair old components. Incremental sheet forming (ISF) is a new forming technology, a fast and flexible process, which is locally deforming metal sheets with a hemispherical tool. An advantage of this technology is the use of simple tooling, a die-less forming process, the reduced forming forces and the equipment capacity [1]. Some variations of ISF, single point and two point incremental forming, have been used in CNC milling machines and was firstly proposed by Mason in his PhD thesis [2].

In Single Point Incremental Forming (SPIF) process, the geometries of sheet metal component are generated through a stable plastic deformation up to the ductile fracture of the sheet. For some materials fracture strains values go above the conventional fracture forming limit in SPIF process and exhibit a better formability compared to the conventional forming technology [3]. The flexibility of the process is assured by the lack of a partial or full die, but some industrial requirements are still a challenge for achieving geometrical accuracy [4].

Deformation mechanism of incremental formed parts and the forming and fracture behavior are still on research with a thorough examination of the process from the perspective of microstructure and crystallographic texture. Aerospace, automotive bio-medical industries have focused more on aluminium and its alloy on their based applications and for their production needs. Adoption of aluminium alloys instead of copper and steel alloys is motivated for its exceptional properties: corrosion resistance, good thermal and electrical conductivity, light weight (high-strength-to-weight ratio) and low cost in comparison to copper [5].

Deformation ability of sheet metals defines formability, a critical material property, which is usually evaluated by a forming limit diagram determined at various forming conditions [6]. Residual stresses of components formed with SPIF technology are influencing fatigue strength and geometrical accuracy. Various studies are

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based on residual stress investigation considering the phenomenological evaluation of the process parameters or the tool path strategy influence on formability [7].

There are various challenges in forming sheet metal parts using advanced technologies because of the process complexity. In this article we emphasize several concerns of the moment regarding incremental forming processes challenges and achievements for increasing formability of different metal sheet materials, predicting failure and optimizing tool path strategies.

2. CHALLENGES IN SHEET METAL FORMING PROCESSES

An experimentally validated mathematical model to predict thickness distribution and formability of incremental forming combined with stretch forming has been proposed for optimization NC coding to achieve components with geometric accuracy by local plastic deformation of thin metal sheets using CNC machines or industrial robots. The forming conditions are chosen at optimum values in the experiments with tool diameter at 5 mm, feed rate at 800 mm/min, step pitch at 0.1 mm for each process equally. Comparing pure incremental forming with hybrid forming with respect to the thickness distributions it has been found that hybrid forming has a more uniform thickness distribution and less thickness reduction [8].

A study regarding deformation behaviors of Cu-Al composite sheets [9] concluded that deformation mode of upper layer sheet tends to a compression state, while that of lower layer sheet tends to a stretching state. The predictive modeling of formability, surface roughness, thickness variation and forming force, and FE simulation and experimental analysis revealed that the overall variation of these parameters is quite similar to that of the single layer materials in SPIF. The forming tool paths used in groove test is in zig-zag to deform the material until a complete crack occurs (Figure 1). The maximum formable angle α_{max} (Figure 2) can be determined by equation (1).

$$\begin{cases} \alpha_{max} = \arccos(y/R) \\ y = h - h_p \end{cases} \tag{1}$$

where R is the radius of generatrix; h is the designed height; h_p is the crack height.

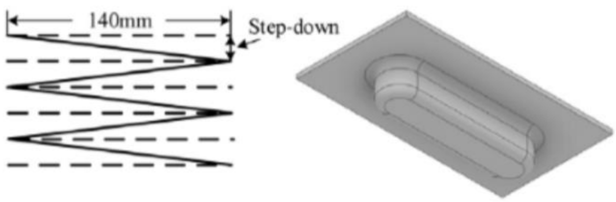

Fig. 1. Designed groove geometry [9].

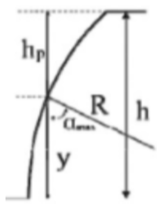

Fig. 2. Groove variable generatrix [9].

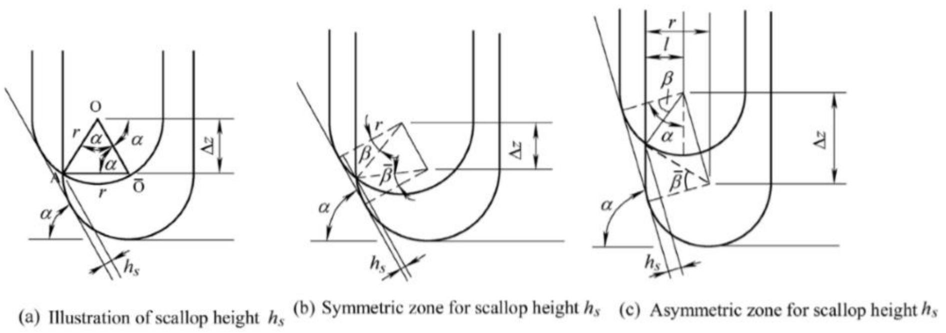

Fig. 3. The geometric relations between scallop height h_s and process parameters (tool radius r, step-down size Δz, drawing angle α) [9].

Scallop height is the peak of waviness caused by two adjacent tool paths with a direct and significant impact on the surface roughness R_z of SPIF parts (Figure 3). This roughness is caused by scallop height and can be approximately measured and predicted with recently proposed analytical model. The proposed model has two situations (Figure 3) and step-down size Δ_z can be calculated with equation (2).

$$\Delta z = r \sin 2\alpha \tag{2}$$

(I) If $\Delta z \leq r \sin 2\alpha$ ($\beta = \bar{\beta}$) as shown in Figure 3 (b), it derives:

$$\sin\beta = \frac{\Delta z}{2r \sin\alpha} \tag{3}$$

$$\cos\beta = 1 - \frac{h_s}{r} \tag{4}$$

Given h_s is far smaller than r, it has:

$$h_s = r - \left(r^2 - \frac{\Delta z^2}{4\sin^2\alpha}\right)^{1/2} \tag{5}$$

(II) When $\Delta z > r \sin 2\alpha$ ($\beta \neq \bar{\beta}$) as shown in Figure 3 (c), it derives:

$$\sin(\alpha - \beta) = \frac{1}{r} \tag{6}$$

$$\cos\beta = 1 - \frac{h_s}{r} \tag{7}$$

$$l = r - \frac{\Delta z}{\tan\alpha} \tag{8}$$

Thickness variation is predicted in single-pass SPIF process with a widely used sine law given in equation:

$$t = t_0 \sin(90^{\circ} - \alpha) \tag{9}$$

where t_0 and t represent the original sheet thickness and deformed sheet thickness; α is the drawing angle.
Based on the statistical method, Aerens et al. [4] proposed a generalized model to predict the axial force, equation (10).

$$F_z = 0.0716 R_m t^{1.57} d^{0.14} \Delta h^{0.09} \alpha \cos\alpha \tag{10}$$

$$\Delta h = \frac{\Delta z^2}{4d \sin^2\alpha} \tag{11}$$

where R_m is the tensile strength (N/mm^2), t is the thickness of the sheet (mm), d is the diameter of the tool (mm), α is the drawing angle (degree), Δh is scaloop height, and Δz represents the step-down size (mm).

For bimetal composite materials, the initial formula is set as given in equation (12).

$$F_z = a d^b \Delta h^c \alpha \cos\alpha \tag{12}$$

where a, b and c are coefficients to be determined by experimental data as given for the vertical steady force in equation (13).

$$F_{zs} = 15.12 d^{0.1951} \Delta h^{0.07665} \alpha \cos\alpha \tag{13}$$

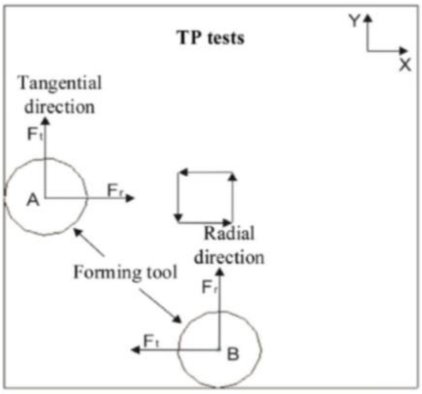

Fig. 4. Illustration of typical forming forces for TP tests [9].

The above equation is obtained after comparison of experimental data in the case of truncated pyramid (TP) test with the original empirical model for vertical steady force prediction (Figure 4). The peak vertical force at the step-down point F_{zp} and the steady vertical force when the tool travels along the z-level tool path F_{zs} represent the vertical (Z) force. The tangential force F_t created by friction force that is opposite to tool travel direction, the steady radial force F_{rs} when the tool travels along the z-level tool path, and the peak radial force F_{rp} at the step-down point, represent the X (Y) force. X force is equal to Y force in TP test because of the symmetric geometry.

An increased formability and geometrical accuracy of the components made in SPIF processes can be otained by increasing sheet thickness, friction and decreasing tool diameter. Maheshwar Dwivedy and Vinayak Kalluri found that sheet thickness and z-depth are the process parameters with the highest influence on forming forces (average radial and peak radial forces) [2]. The quantitative contribution of each deformation mode (membrane stretching, bending and thickness shear) at various locations of a part formed by SPIF is determined as a function of the process parameters by Fawad Maqbool and Markus Bambach in [4].

3. RECENT ACHIEVEMENTS IN SHEET METAL FORMING RESEARCH

The highest formability obtained in sheet metal forming is given by the incremental sheet forming processes being of interest for rapid prototyping and small batch production. The forming fracture limit is delayed in these processes because the plastic strain in the obtained part is distributed more evenly than in deep drawing [10].

Single point incremental forming (SPIF) faces some challenges with lightweight alloys because of macroscopic cracks while forming components with desired geometry. Recent researches are concentrated on specific studies to predict fracture in SPIF and provide references for the practical SPIF process [1]. Xuepeng Zang et al. are using a numerical method, anisotropic ductile fracture model, to predict failure in SPIF based on the HU-Chen ductile fracture criterion, and modified by using Hill48 anisotropic yield criterion. Lightweight and strength materials as ultra-high strength steels are required in aircraft and automotive industries to reduce structural gauge and vehicle weight. For stretching ultra-high strength steels have been made studies on modelling methods to achieve formability prediction [6]. For bending dual phase steels, it is necessary to apply high forming forces as these materials exhibit limited ductility prior to fracture which is often smaller than 10-15% [11].

The formability of sheet materials is given by the failure strain and the maximum achievable draw angle. The wall angle is generally used for comparison of different materials formability by forming multiple cones with successive increasing wall angle until failure occurs. In formability studies, the reference for draw angle varies between 60 to 70 degrees in the case of steel and aluminum alloys sheet materials. A 0.93 mm thick AA5754-O sheet is incremental formed by a multi-pass technique with a maximum draw angle of 62° and the lowest thickness obtained is at a radial distance of 32 mm and 35 mm corresponding to the Inside-Out steps, which is a better formability than predicted by simple models like Sine Law. After applying a method for predicting rigid body motion (RBM) in multi-pass single point incremental forming (MSPIF), authors claim a better formability of the sheet metal part with an increase in the maximum wall angle of approximately 15° relative to single stage forming [12].

A C-channel designed for the vibrational testing of airplane fuselage system (Figure5), was developed through trial and error using multi-stage tool path strategy. The conditions for the experiments were chosen based on the expertise developed in the laboratory and implies a helical toolpath, a tool step of 0.2 mm, rotation speed of 500 rpm, feed rate of 5000 mm/min, with a flat tool of 9 mm diameter and a corner radius of 3 mm forming AA3003 sheets with 2.54 mm thick. The maximum draw wall angle ranged between 84.80° and 85.01° for a variable wall angled geometry with major diameter of 177 mm and a minor diameter of 142 mm. In the cross-sectional analysis (Figure 6) are revealed major thickness variations from 2.54 mm in region 1, 0.5 mm in region 5 and 2.2 mm in region 11 [13].

In the experimental process of DC01 steel sheets with 1.0 mm thickness has been obtained a maximum angle of 67° for a cone SPIF geometry of 30 mm depth. Some models to predict failure during SPIF have been analyzed to compare with experimental results. An extended Gurson model and a Lemaitre and Chaboche model have been applied to study formability of a truncated cone geometry made of DC01 steel sheet. In the Chaboche an Lamaitre model are better results in failure prediction (57°) than the GTN model (47° or 51°) because of the latest inability to describe the strain localization and the associated thinning of the sheet metal in the coalescence regime [8].

Fig. 5. Manufactured component [13].

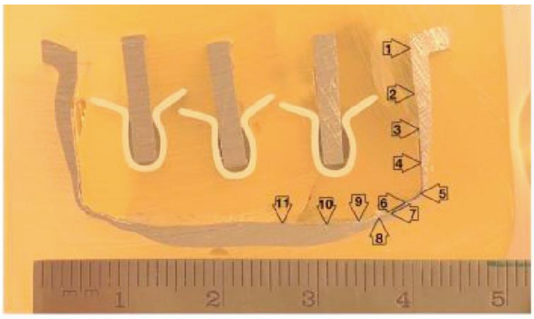

Fig. 6. Cross-section of a developed component [13].

The influence of tool path strategy on residual stress is given by two process parameters: tool radius and vertical step-down increment. A validated numerical model is proposed applying unidirectional and bidirectional tool path strategies (Figure 7) on aluminium alloy 5083 sheets to form linear grooves. The effect of tool path strategy on the residual stress amplitude can be neglected for the linear groove geometry (Figure 8). The investigated relative step-down range is at the highest residual stress amplitude where the shearing ratio is on a low level than of the high bending ratio [7].

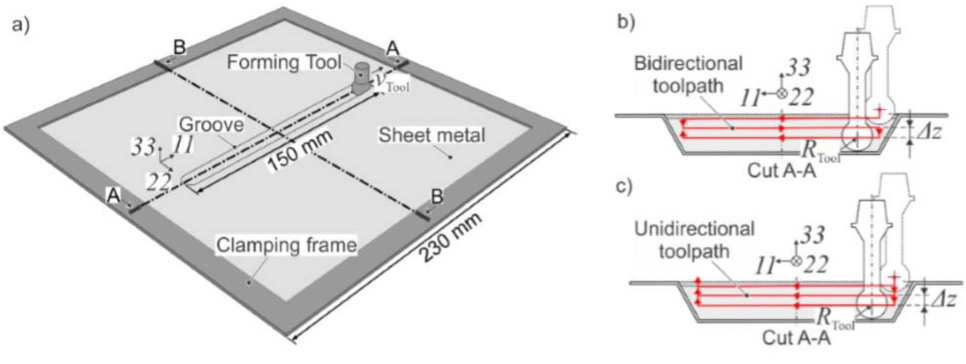

Fig. 7. (a) experimental setup; (b) bidirectional tool path strategy; (c) unidirectional tool path strategy [7].

Fracture behavior of titanium grade 2 and Ti–6Al–4V has been studied using SPIF for it's widely uses form of titanium alloys in aerospace applications and medical implants. For the experimental tests has been varied the tool diameter, speed with a feed rate of 300 mm/min and vertical step depth. The obtained Fracture Limit Curve has been revealed the limiting maximum fracture strain values at a maximum speed of 600 rpm and a tool diameter of 12 mm. There is a direct dependency between the increase and decrease of speed and vertical step depth with limiting major true strain value as obtained in the Forming Limit Diagram [14].

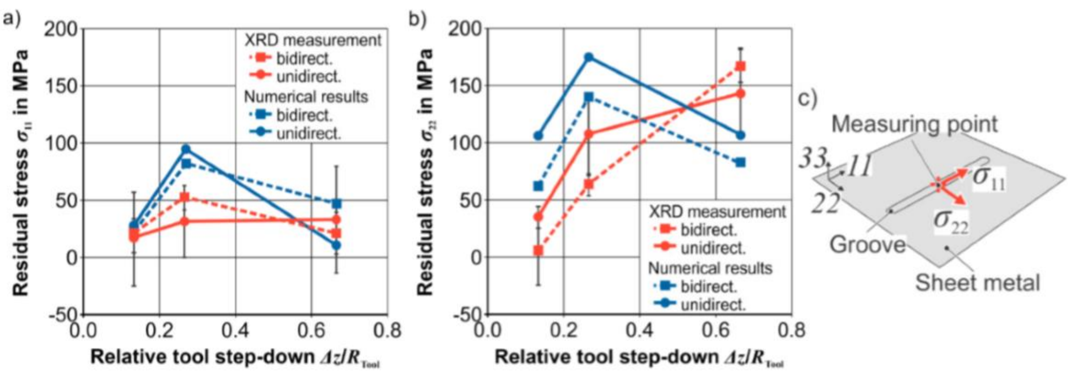

Fig. 8. Residual stress development on tool-side with increasing relative vertical step-down increment $\Delta z/R_{tool}$: (a) tool path direction; (b) transverse to the tool path direction; (c) measuring point in the groove center [7].

4. FUTURE REASEARCH DIRECTIONS

In multi-pass incremental forming (MIF) of sheet metals, there is a concern regarding tool path optimization to obtain a better formability. A methodology has been proposed for an axisymmetric cone toolpath with a generic framework which authors recommend it to be extended for other MSPIF toolpaths. Also, it is of high importance to use a rigid tool for incremental forming so that the material properties have a negligible effect on the rigid body motion [12].

Some findings of recent proposed models that predict failure during SPIF process are expected to be improved if the failure prediction results would be partially included in the identification process or using an advanced optimization algorithm [10].

SPIF process can’t form vertical walls in a single pass. Multi-stage toolpath strategy is continuously optimized by research community to achieve formability and complexity in component geometry. Multi-stage incremental forming is used for high wall angles but is a concern because of the high thickness variation and necessitates the employment of trial and error methods used by a knowledgeable engineer [13].

Although aluminium is the most used material in aerospace and automotive industry, there is a widely use of titanium alloys in these industries for their high strength compared to weight ratio and a good corrosion resistance compared to aluminium and steel. Titanium grade 5 sheet material (Ti-6Al-4V) is used in approximately 80% of the titanium (alpha-beta) alloy used in USA. But it’s low formability compared to titanium grade 2 makes the interest for the latest to increase in academic and industry community. It has been experimentally proven that in SPIF process the rotational shear stress is influencing void coalescence, growth and length wise fracture of titanium grade 2 sheet materials [14]. Further research for optimizing formability of titanium alloys would be necessary.

Hybrid forming processes which combine incremental forming with stretch forming have a growing interest because of the lower thickness reduction and more uniform thickness distribution than pure incremental forming. Besides, applying optimum conditions in hybrid forming it is obtained a more endurance stress than the pure incremental forming [8].

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