PROCESS SIMULATION AND QUALITY EVALUATION OF INCREMENTAL SHEET FORMING

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ABSTRACT: Single Point Incremental Forming (SPIF) is a promising sheet-metal-forming process that permits the manufacturing of small to medium-sized batches of complex parts at low cost. It allows metal forming to work in the critical 'necking-to-tearing' zone which results in a strong thinning before failure if the process is well designed. Moreover, the process is complex due to the number of variables involved. Thus, it is not possible to consider that the process has been well assessed; several remaining aspects need to be clarified. The objective of the present paper is to study some of these aspects, namely, the phenomenon of the wall thickness overstretch along depth and the effect of the tool path on the distribution of the wall thickness using finite element simulations.

ABSTRAK: Pembentukan Tokokan Mata Tunggal (*Single Point Incremental Forming (SPIF))* merupakan satu proses pembentukan kepingan logam yang membolehkan pembuatan dalam jumlah yang kecil hingga sederhana, bahagian-bahagian yang kompleks pada kos yang rendah. Jika proses ini direka dengan baik, kaedah ini membolehkan pembentukan logam yang baik terhasil. Jika tidak, semasa peringkat zon kritikal 'perleheran-ke-pengoyakan' menyebabkan penipisan keterlaluan yang boleh menyebabkan logam tersebut rosak. Tambahan pula, proses ini agak kompleks, kerana ia melibatkan beberapa pemboleh ubah. Maka, walaupun proses ini telah dinilaikan seeloknya; masih terdapat beberapa aspek lain yang perlu diperjelaskan. Objektif kertas ini dibentangkan adalah untuk mengkaji beberapa aspek tertentu, seperti, ketebalan dinding regangan berlebihan di sepanjang kedalaman dan kesan *tool path* (beberapa siri posisi koordinat untuk menentukan pergerakan alatan memotong ketika operasi memesin) terhadap pengagihan ketebalan dinding menggunakan simulasi unsur terhingga.

KEYWORDS: *incremental sheet forming; finite element method; LS-Dyna; alumunium; thickness distribution*

1. INTRODUCTION

Nowadays, many industrial sections use forming processes like deep drawing and stamping in order to manufacture sheet metal components with high productivity. These processes need large initial investments and long die-preparation times, with specific dies for each part, particularly when the parts have complex shapes or are only needed in small series, as is the case with unique aeronautic and automotive parts. Therefore, there is a need for a flexible technology that is also viable for small and medium-sized enterprises. Incremental sheet forming (ISF) is a new process for manufacturing sheet metal parts which is well suited for small batch production or prototyping [1, 2].

In order to use this process on a large scale, some aspects of the process need to be further clarified. Therefore, the objective of this paper is to investigate the use of the finite element (FE) method to predict thickness and stress distribution on the sheet during forming in order to improve the knowledge of the ISF process.

The remainder of this paper is structured as follows: an overview of the incremental sheet forming process is given in Section 2. The limitations of the process are addressed in Section 3. Section 4 elaborates the process formability analysis in this simulation-based investigation and the finite element results are reported in Section 5. Drawn conclusions are contained in Section 6.

2. OVERVIEW OF THE ISF PROCESS

Incremental sheet forming is relatively a new process capable of producing complex sheet parts by the movement of a single point tool mounted on a standard 3-axis CNC machine without dedicated dies as shown in Fig. 1. In order to avoid excessive thinning for parts having almost straight wall angles (wall angles greater than 60°), multistage forming strategies have to be used [3]. Compared to traditional sheet forming processes, the single point incremental forming (SPIF) process enables much higher strains. When SPIF is applied to single stage formations, it is limited by deformation types that are near the strain plane.

Fig. 1: Incremental sheet metal forming process [4].

Existing experimental configurations for incremental forming can be put into two general types: negative and positive incremental forming. Negative die-less incremental forming, also known as single point incremental forming (SPIF) as illustrated in Fig. 2, is the first form of incremental forming.

Single Point Incremental forming was developed in recent years as an innovative numerically controlled sheet metal forming technology [5, 6]. For small batches, as small as a single exemplar, it is a very economical process.

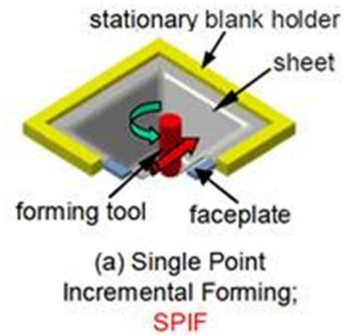

Fig. 2: Single Point Incremental Forming (SPIF) [7].

Many application fields are considering this innovative technology, among them are automotive manufacturing [8], manufacturing of customized medical products [9], and automotive sheet metal forming, specifically the calibration of the void nucleation model [10]. The process is categorized as ‘‘Negative and Positive Incremental Forming’’ [11]. Localized deformation [12] is a key feature of this technology because it enhances sheet-metal formability. For incremental forming, the forming limit diagram has a limit curve that is a straight, negative slope line within the stretching region [13, 14].

As shown in Fig. 3, the blank is firmly clamped to the fixture. The tool used to form can be programmed in the three axes of translation along with spindle rotation. The form-giving tool representing the required shape remains stationary throughout the process. Using a suitable tool path strategy, the forming tool moves around the form-giving tool, from top to bottom. It covers the component level by level, in the predefined vertical increments, in contact with the blank and incrementally deforming the blank until the desired shape has been formed. Thus, a CNC controlled movement of a universally usable forming tool produces the desired shape.

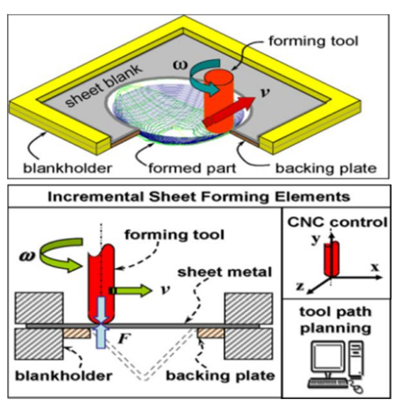

Fig. 3: The working principle of SPIF [15].

3. LIMITATIONS OF INCREMENTAL FORMING

The final thickness of a part formed by SPIF can be estimated using the sine-law. This law was originally developed for the shear forming process and simply states that:

$$t_1 = t_0 \sin\left(\frac{\pi}{2} - \alpha\right) \quad (1)$$

where t_0 is the initial thickness, t_1 the final thickness, and α the wall-angle measured with respect to the horizontal. This law is illustrated in Fig. 4; it describes the thickness distribution well and shows that parts with drawing angles greater than 60-80° in one stage are not achievable.

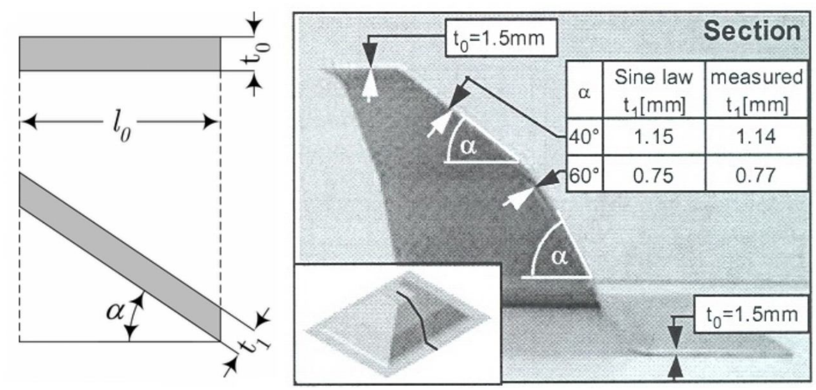

Fig. 4: Prediction of the thickness in SPIF using the sine law [16].

The sine law is based on the fact that the material is approximately in a plane strain state in the direction of the tool movement and is only able to move vertically toward its final position when starting from a horizontal flat sheet. As shown in Fig. 4, the comparison between the measured thickness and the one predicted by the sine law is very good.

A direct consequence of the sine law is that the thickness decreases as the angle increases, as illustrated in Fig. 5. In particular, the theoretical thickness of a part with vertical walls would be zero. The wall angle is a major limitation of SPIF [17]. The limitation in the maximum wall angle is only valid for parts formed in one pass, i.e., when the tool follows the shape of the final geometry. Other strategies have been developed to overcome this limitation.

Using a multi stage strategy is one way to circumvent the limitations imposed by the sine-law. Using such a strategy has been attempted before in SPIF. Kitazawa [19] used various two stage strategies in the production of hemi ellipsoidal shapes, while varying the radius and height of the shape in order to determine the fracture limits. Here, the intent is to extend deformation across all the material indicated by the curved lines and then to identify the effect of the said extension. The first stage stretches the sheet until the end of the part depth. The next stages gradually shift the middle of this section towards the corner.

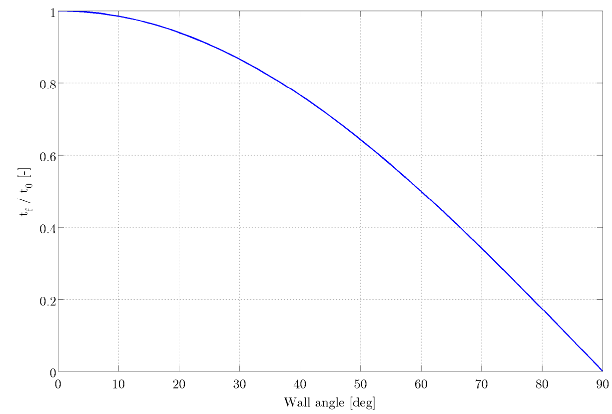

Fig. 5: Thickness reduction in SPIF as predicted by the sine law [18].

4. FORMABILITY ANALYSIS

Areas requiring more investigation remain within the ISF research field. Two such areas are material formability and a complete understanding of process mechanics. With respect to process knowledge, many improvements have been introduced in the form of simple laws suited to industrial use. From the literature review [20, 21], primarily, two parameters are used to classify the process formability, namely:

- the α max, representing the maximum wall slope angle at which the part can be manufactured without damage;
- the FLD_0 point, corresponding to the intersection of the FLC and the major strain axis.

Sadly, the complexity of the process creates recognizable drawbacks based on those same two parameters. Firstly, both parameter values depend directly on the process parameters that were adopted so that they cannot describe the whole process synthetically. Secondly, while α max is an easier parameter to work with industrially, it only provides a partial description of the overall process feasibility. In fact, there have been applications where parts with complex geometries and variable slope walls were successfully manufactured with angles greater than the critical angle, despite the presence of angles greater than critical angle [22].

5. SIMULATION AND RESULTS

Incremental forming processes can be simulated by a series of steps including:

- Building CAD models (support, tool blank, , part with desired shape);
- Generating tool-paths for controlling the tool movement;
- Building finite element model, applying boundary conditions, defining material properties, contact parameters etc;
- Solving model, post processing.

The second step, tool-path generation, may not be necessary for the simulation of forming processes on metals. However, when simulating incremental forming, tool path generation will create a pre-defined trajectory for the tool. For simple cases, the tool path can be generated using a simple spreadsheet program. For more elaborate forms, as in the current study, a (CAD/CAM) Computer Automated Manufacturing system (CATIA) is used.

Finite element analysis of the metal forming step was performed to avoid the possibility of multiple trials and errors and therefore save costs and time. In this work, the SPIF process was simulated using ANSYS/LS-DYNA version ls971s. The forming tool and the backing plate are set as rigid. Five integration points are used for the thickness simulation of fully integrated shells (type 16 in DYNA). Adaptive re-meshing is adopted. The simulated tool movement matches real experiments including aspects such as rotation. Aluminum AA1050 H111/O is used as sheet metal and it is considered isotropic with a flow stress. The Coulomb friction coefficient was assumed to be equal to 0.1. Forming tools with a semi-spherical tip have a radius of 6 mm.

5.1 Depth Overstretch

First and second stages have a fixed vertical step size of 0.5 mm. Figure 6 shows the geometries used in both stages with h = 82.5 mm and r = 82.5 mm.

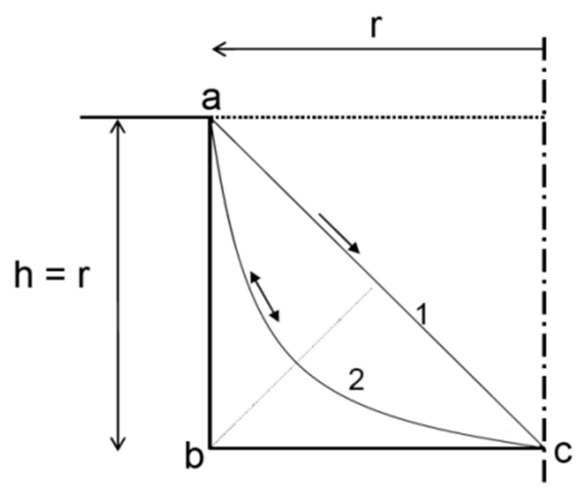

Fig. 6: Two-stage strategy for forming a cup.

An undesirable phenomenon was observed during simulation. In the second forming stage, a small plateau was formed below the tool as it moved downward. As a result, a residual cone was formed in the bottom of the cup. The defect is created as the depth of the cup was increased during the second stage but the tool path remained at 82.5 mm. The residual cone can be seen in Fig. 7, and it was measured to be approximately 20 mm too deep.

To avoid the stretch downwards and to get the desired depth a small un-deformed section remains in the first stage with depth of 40 mm whereas the part is fully deformed in the second stage until the depth of 82.5 mm as shown in Fig. 8.

5.2 Wall Thickness Reduction

It is found that sheet metal formability is dependent on slope along the bottom (depth) of the fabricated part. If the slope changes along the depth, then the shell thickness is reduced at a faster rate than a case with a fixed slope.

Forming process has been simulated using five stages as shown in Fig. 9. The first three stages have fixed slope. The first stage has forming angle of 20° with depth of 20 mm whereas the second stage has an angle of 30° with depth of 40 mm.

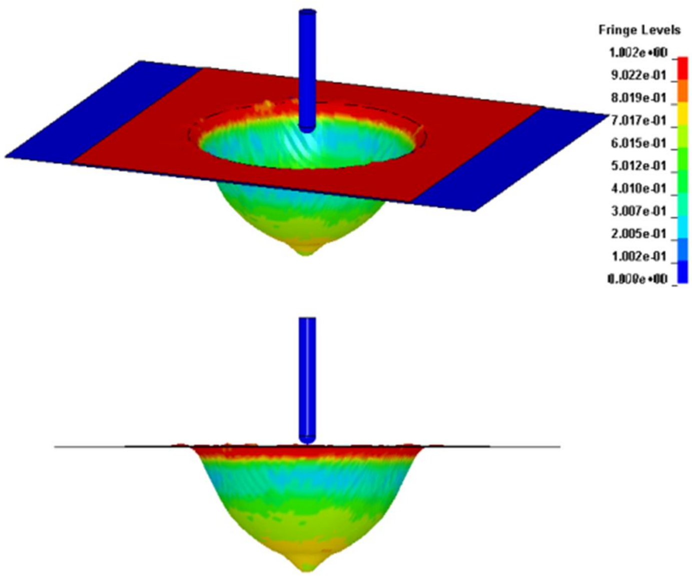

Fig. **7**: Residual cone in the center.

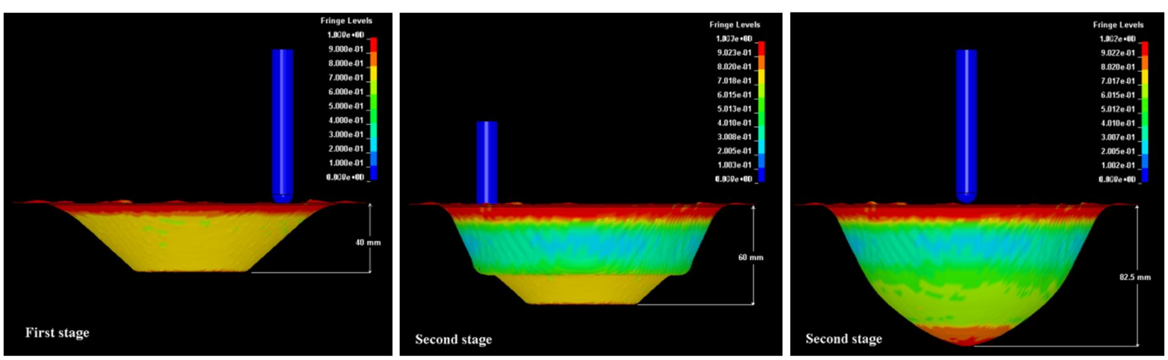

Fig. 8: Modified two stage strategy for forming the cup.

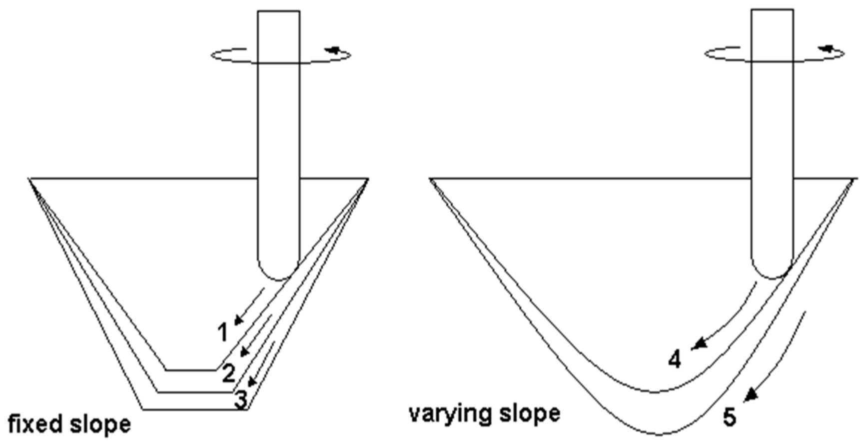

Fig. 9: Five stage forming process.

The depth of the third stage has 60 mm with forming angle of 40°. Starting from the fourth stage the forming tool goes down 80 mm with parabolic curve and the last stage with circular curve and 82.5 mm deep.

Among varying slope parts (formed with a curved line) those that were formed with parabolic trajectories (4^{th} stage) exhibited the best forming limits of the sheet-metal without sharp reduction of the sheet thickness as shown in Fig. 10. The parabolic curve parts had consistently higher thinning limits and forming angle limits than those with any form of constant forming angles or slopes. As a result, parts with varying slope can be formed without making the wall thickness very thin. On the other hand, parts with fixed slopes along the depth cause sharp thinning along wall thickness. Moreover, switching from fixed slope to varying slope reduces the thinning of the sheet and the possibility of having crack.

Figure 11 shows the relation between the thickness and the depth of the formed part. Most of the thinning occurs at the center of the part where there is a low drawing angle, which is necessary in order to achieve vertical sides in subsequent stages.

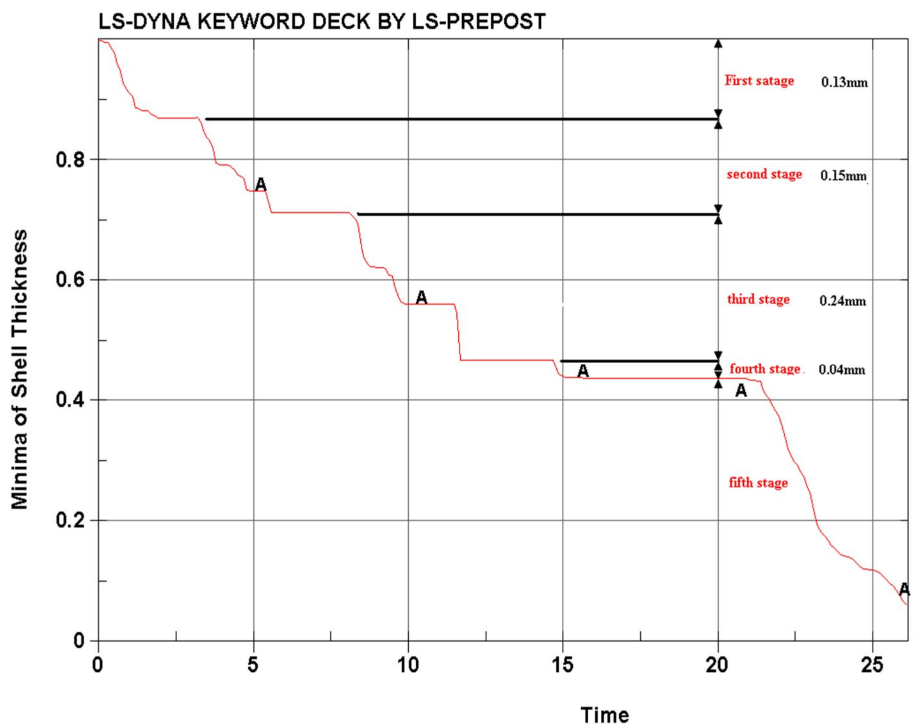

Fig. 10: Wall thickness distributions as function of time.

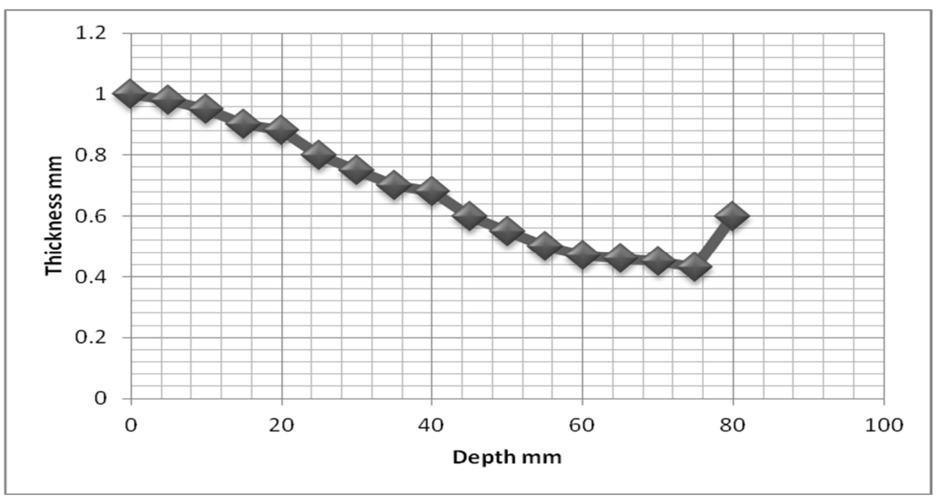

Fig. 11: Thickness as a function of depth.

Theoretically, the dependence between the sheet metal's formability and the slope distribution used to create it can be shown. For two parts, one with variable slope as described in Fig. 12a and another with a fixed slope as described in Fig. 12b, both created by Incremental Forming. The resultant forming force is denoted by F, and the instantaneous position of the tool is denoted by N. In the case of the variable slope (Fig. 12a), the component force $F\sin\theta$ is acting on a subset of the MN curve, called segment LN. In the case of the fixed slope (Fig. 12b), the entire MN curve undergoes the same component force $F\sin\theta$. The constant force weakens the MN segment far more than the changing forces in the first case. Correspondingly, the constant force causes greater thinning within the walls of the part.

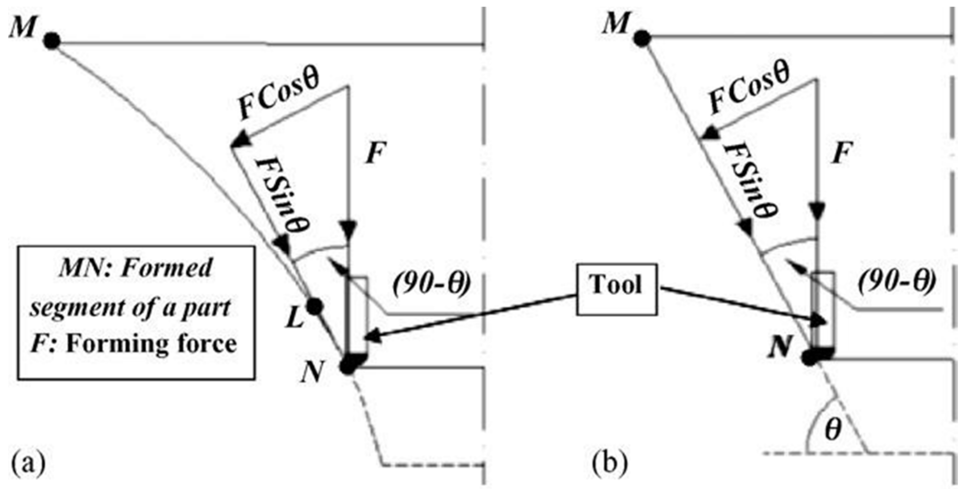

Fig. 12: Forming forces required to form: (a) Parts with varying slope and (b) parts with fixed slope along depth. [23].

6. CONCLUSION

When incremental forming techniques are applied to sheet metals, formability is dependent on the slope distribution during the formation of a part. A variable slope along the depth of the part has a great effect on the wall thickness, or in other words it depends upon how the forming of the sheet changes during the process from fixed slope to varying slope to minimize the thinning of the sheet. Thus, such mechanism can enhance the dimensional accuracy and delay the fracture. Consequently, this will give the chance to form the sheet in a high forming angle such as 90°.

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NOMENCLATURE

ISF	Incremental Sheet Forming
SPIF	Single Point Incremental Forming
CAD	Computer Added Design
CAM	Computer Added Manufacturing
FLD	Forming Limit Diagram
FLC	Forming Limit Curves
CNC	Computer Numerical Controller