# FORMABILITY STUDY AND FORMING PATH OPTIMIZATION IN SINGLE-POINT INCREMENTAL FORMING PROCESS

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**ABSTRACT:** This paper analyzed the formability of Aluminum sheet metal in single-point incremental forming (SPIF) numerically and the effect of the feed rate, the vertical feed (pitch) and the spindle revolution on the formability. Two methods were utilized to enhance the formability in SPIF process. In these approaches, variation of vertical pitch was considered and the effects of this parameter on the strain distribution and formability were analyzed. It is found that these methods normalized the strain distribution and improved the formability. Finite element method (FEM) with the aid of design of experiments (DOE) technique was used for predicting the parameters effects and optimizing the forming path. Experiments were also carried out to verify the validity of numerical results.

**KEYWORDS**: *Single-point Incremental Forming (SPIF), Finite Element Method (FEM), Design of Experiments (DOE), formability, forming path.*

## 1.0 INTRODUCTION

Incremental sheet forming (ISF) is a novel process which allows producing complex sheet components by programmed movement of a simple tool, with or without use of dies. In single-point incremental forming, blank is completely clamped by a fixture. A hemispherical head tool moves along programmed contours on the blank and forms it through small localized deformations.

Parameter study is a debatable issue in many researches done on single-point incremental forming process. Hussain et al. [1] investigated the effect of some process parameters such as pitch size, tool diameter, feed rate and friction at the interface between the tool and sheet. Petek et al. [2] presented the analysis of some influential parameters on the deformation size and forming force in single-point incremental forming process. They showed that the deformation and forming force mainly depend on wall angle, tool diameter and vertical pitch size of tool. Rattanachan and Chungchoo [3] examined the tool effective speed influences on formability in single-point incremental forming process. The results show that the tool rotational speed and the feed rate affect the formability of sheet metal. Single-point incremental forming at high feed rates and tool rotational speeds has been examined by Hamilton and Jeswiet [4]. Arfa et al. [5] focused on the influence of four process parameters incuding the initial sheet thickness, the wall angle, the workpiece geometry and the tool path contours. Ambrogio et al. [6] investigated the effect of the feed increasing on the material quality in single-point incremental forming.

Formability in single point incremental forming (SPIF) and thickness distribution attract many researchers' attention and some works have been done in this field. Martins et al. [7] presented a theoretical model for different modes of deformation commonly found in SPIF. Hussain et al. [8] explored the most relevant material property capable of being used as an overall indicator of the SPIFability. The percent tensile reduction of the area holds a consistent relation with the SPIFability and, therefore, can be used as a formability indicator in the SPIF process. LI et al. [9] investigated the thickness distribution and mechanical property of a truncated pyramid processed by incremental forming. Malhotra et al. [10] used a fracture model to predict the occurrence of fracture in SPIF.

The generation of the tool path is of particular interest as it defines attributes such as surface finish, forming limits, processing time, and thickness variation. To cite an instance, the effect of tool path on deformation behavior is examined with respect to several tool paths by Yamashita et al. [11]. Hrairi and Echrif [12] examined the wall thickness overstretch along depth and the effect of the tool path on the distribution of the wall thickness. Azaouzi and Lebaal [13] developed a parameterized forming strategy for the tool path optimization in single-point incremental sheet forming. They presented an optimization procedure to reduce the manufacturing time and homogenized thickness distribution of an asymmetric pattern. Fu et al. [14] developed an algorithm for the tool path correction of single-point incremental forming.

In this paper, the formability of Aluminum sheet in single-point incremental forming (SPIF) was investigated numerically and the effects of some influential parameters on the formability were examine. Considering variable vertical pitch, two methods are presented to enhance the formability of sheet in SPIF process. Experiments were also carried out to verify the validity of numerical results.

## 2.0 FINITE ELEMENT ANALYSIS

An asymmetric square blank with 110mm×110mm dimension was analyzed based on the SPIF process of a pyramid (Figure 1 and Table 1). The sheet was clamped between a fixed square blank holder and a stationary die and the shape of blank holder and die were the same indeed. A 10 mm diameter forming tool with spherical head was used to form the sheet by a continuous movement. The blank was made of 0.3 mm thick Al 1050-O fully annealed sheet. The material properties of sheet are listed in Table 2. Friction coefficient at the tool–sheet interface was specified as 0.15.

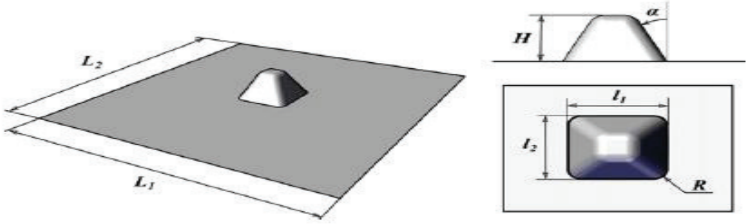

Figure 1: Dimensional parameters of blank and pyramidal workpiece.

Table 1: Geometrical parameters of the pyramidal workpiece.

| $L_1$ (mm) | $L_2$ (mm) | $l_1$ (mm) | $l_2$ (mm) | H (mm) | R (mm) | $\alpha$ (deg) |
|---|---|---|---|---|---|---|
| 110 | 110 | 90 | 90 | Variable | 1 | Variable |

Table 2: material properties of Al 1050-O sheet

| Parameter | Value(Unit) |
|---|---|
| Young modulus (E) | 69 (GPa) |
| Density ($\rho$) | 2700 (Kg/m$^3$) |
| Yield strength | 35 (MPa) |
| Ultimate tensile strength | 80 (MPa) |
| Poisson ratio | 0.33 |
| Strength coefficient(K)* | 140 (MPa) |
| Strain hardening exponent (n)* | 0.25 |

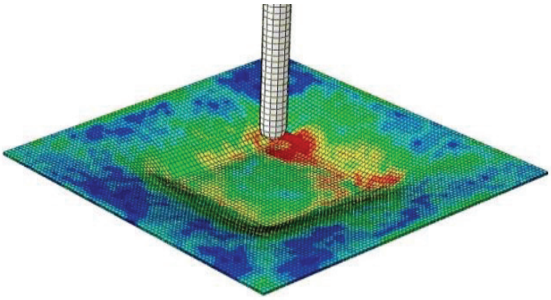

Figure 2: FEM Model for single-point incremental forming

A three-dimensional FEM was established for the multiple step incremental forming and an explicit analysis was conducted. The FEM model is shown in Figure 2. The forming tool was permitted to move along x, y and z directions. It was also allowed to rotate around its axis, z-axis. The number of blank elements was 145200 and linear hexahedral elements (ABAQUS type C3D8R) with mesh size of 0.5 mm including 3 layers were used. Blank holder and die were supposed to be analytical rigid surface and the forming tool was considered discrete rigid with a total number of 3317 elements. Forming force method was used to detect failure onset. Hence, the failure has been detected by a sudden decrease in force trend.

## 3.0 EXPERIMENTAL PROCEDURE

### 3.1 Design of experiments

Taguchi method was used to explore the most influential factors and to show the impact of effective factors variations on the formability. Three parameters namely the feed rate, the revolution speed of the forming tool and the vertical pitch were discussed. Values of forming parameter were chosen for three levels (refer to Table 3). An L9 orthogonal array with three columns and nine rows was used. The design of experiments is shown in Table 4.

Table 3: single-point incremental forming parameters

| Symbol | Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| A | Feed rate (mm/min) | 250 | 500 | 750 |
| B | Revolution speed (rev/min) | 500 | 800 | 1250 |
| C | Step pitch (mm) | 0.95 | 1.05 | 1.15 |

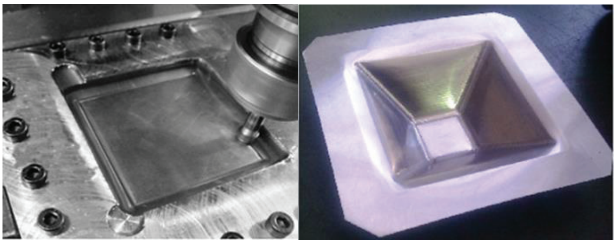

Figure 3: Experimental set-up and a pyramidal workpiece formed by single-point incremental forming

Table 4: Design of experiments

| Exp. No. | A | B | C |
|---|---|---|---|
| 1 | 250 | 500 | 0.95 |
| 2 | 250 | 800 | 1.05 |
| 3 | 250 | 1250 | 1.15 |
| 4 | 500 | 500 | 1.05 |
| 5 | 500 | 800 | 1.15 |
| 6 | 500 | 1250 | 0.95 |
| 7 | 750 | 500 | 1.15 |
| 8 | 750 | 800 | 0.95 |
| 9 | 750 | 1250 | 1.05 |

## 3.2 Experimental work

Geometrical parameters of the workpiece are the same as numerical simulation. Al 1050-O sheets with 0.3mm thickness were used in the experimental study (Table 2). The sequence of experiments was performed (refer to Table 4). The tests were conducted in a fixed environmental situation. The experimental set up and a pyramid formed in experimental study are shown in Figure 3.

## 4.0 FORMING PATH OPTIMIZATION

In order to study the deformation behavior, four levels were considered (Figure 4). After the tool passed the first level, only the elements of this level experienced deformation. When the punch reaches level 2, first level elements will be stretched again beside the elements in second level. In other words, the stretching in level 2 affects considerably on the strain trend in level 1. In the same way, level 3 increases level 1 and level 2 strain values.

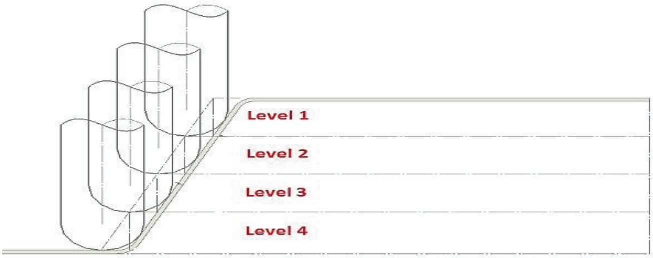

Figure 4: Supposed forming levels

Consequently, with constant vertical feed, it can be expected that top levels had more strain magnitudes in comparison with lower levels. As the higher strain values accelerated fracture occurrence, minimum strain amount was desirable. In this paper, investigation over this issue led to the fact that changing vertical feed normalized strain distribution. Fortunately, the desirable situation, moving toward normalized strain distribution, was accessible with the aid of optimization procedures. With this purpose, two methods were introduced and reasonable results were presented.

Table 5: Forming parameters for method I

| Level | Parameter | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ |
|---|---|---|---|---|---|
| Level 1 | pitch (mm) | 0.7 | 0.7 | 0.7 | 0.7 |
| Level 2 | pitch (mm) | 0.9 | 0.9 | 0.9 | 0.9 |
| Level 3 | pitch (mm) | 1.1 | 1.1 | 1.1 | 1.1 |
| Level 4 | pitch (mm) | 1.3 | 1.3 | 1.3 | 1.3 |

## 4.1 Method I

In this method a SPIF process with 4mm depth was considered. The vertical feed was considered to vary in various steps of the process. Four pitch variables in Z-direction and four values (levels) for each variable were regarded (Tables 5). The summation of these four parameters in each experiment was equal to 4mm. All possible setups were simulated in finite element software and analyzed with statistical approach through Taguchi method. The equivalent plastic strains of corner elements were measured and then means of these strains were calculated.

## 4.2 Method II

In this initiative method, a new approach called ‘forming path angle (FPA)’ was presented. A connecting line, which was passing from the tool tips at the beginning of different forming levels just before the vertical feed and after the motion along x and y directions, was considered. The angle that this line made with the horizontal axis was forming path angle. When FPA and wall angle were the same, forming process was carried out with constant vertical feed (Figure 5). It is possible to have a variety of vertical feeds by changing FPA, as shown in Figure 6. Therefore, a wide range of vertical feeds was accessible.

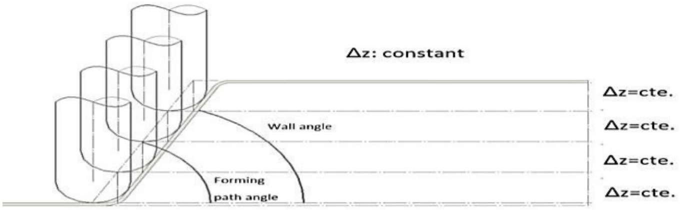

Figure 5: Forming path angle with constant pitch

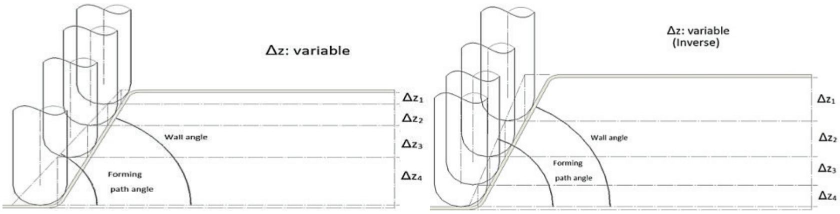

Figure 6: Forming path angle with increasing and decreasing pitch

Two criteria were presented for finding the best vertical feed:

1. The smallest difference between the maximum and minimum equivalent plastic strain (EQPE).
2. The smallest strain between the maximum EQPEs.

## 5.0 RESULTS AND DISCUSSION

### 5.1 Comparison of experimental and numerical results

Moving average trend lines for force diagrams in experimental and numerical work can be seen in Figure 7. A comparison of experimental and FEM force curves showed a considerable agreement in the force patterns. The peaks occurred when the tool was at the corner of the pyramid and higher peaks occurred when the tool was performing the vertical step downwards.

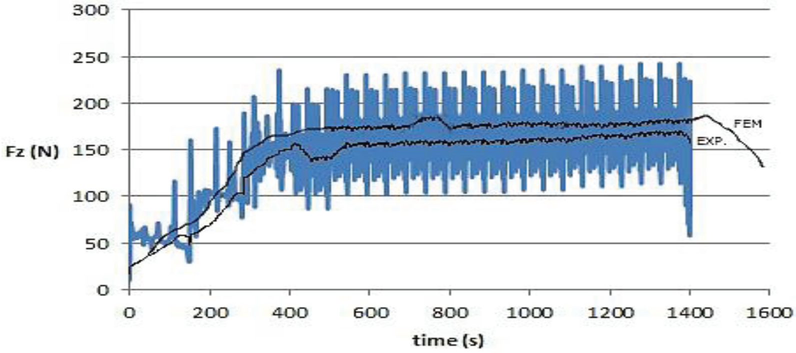

Figure 7: Comparison of experimental and numerical forming force

## 5.2 Analyzing and Evaluating Results of Experiments Using the Taguchi Method

The experimental and numerical forming limits in the form of failure depth are shown in Table 6. Level values of the factors obtained from the mean responses are in accordance with the Taguchi design, and factor ranking for numerical and experimental data are given in Table 7 and Table 8. Figures 8 and 9 show the main effects plot (data means) for means of means separately. Hence, the experimental and numerical results had an obvious accordance.

The step pitch was a factor which had the biggest difference between means values in numerical and experimental works, 1.27 and 1.383, respectively. Based on the Taguchi method prediction, the larger difference between the values of means, the more considerable effect on the formability. Thus, it can be concluded that decreasing the vertical height increased the formability significantly. Revolution speed and feed rate were in the lower ranks. The optimum forming conditions, which were the feed rate of 250 mm/min, the revolution speed of 500 rev/min and the pitch of 0.95 mm were obtained for the best response values.

Table 6: Comparison of final depth obtained experimentally and numerically

| Exp. No. | A | B | C | Experimental Final depth (mm) | Numerical Final depth (mm) |
|---|---|---|---|---|---|
| 1 | 250 | 500 | 0.95 | 9.50 | 13.8 |
| 2 | 250 | 800 | 1.05 | 9.20 | 13.1 |
| 3 | 250 | 1250 | 1.15 | 6.90 | 11.2 |
| 4 | 500 | 500 | 1.05 | 8.40 | 12.2 |
| 5 | 500 | 800 | 1.15 | 8.05 | 12.0 |
| 6 | 500 | 1250 | 0.95 | 9.30 | 13.3 |
| 7 | 750 | 500 | 1.15 | 8.25 | 12.6 |
| 8 | 750 | 800 | 0.95 | 8.55 | 12.5 |
| 9 | 750 | 1250 | 1.05 | 8.40 | 12.3 |

Table 7: Response table for means (numerical approach)

| Level | Feed rate (mm/min) | Revolution speed (rev/min) | Pitch (mm) |
|---|---|---|---|
| 1 | 12.70 | 12.87 | 13.20 |
| 2 | 12.50 | 12.53 | 12.53 |
| 3 | 12.47 | 12.27 | 11.93 |
| Δ | 0.23 | 0.60 | 1.27 |
| Rank | 3 | 2 | 1 |

Table 8: Response Table for means (experimental approach)

| Level | Feed rate (mm/min) | Revolution speed (rev/min) | Pitch (mm) |
|---|---|---|---|
| 1 | 8.533 | 8.717 | 9.117 |
| 2 | 8.583 | 8.600 | 8.667 |
| 3 | 8.400 | 8.200 | 7.733 |
| Δ | 0.183 | 0.517 | 1.383 |
| Rank | 3 | 2 | 1 |

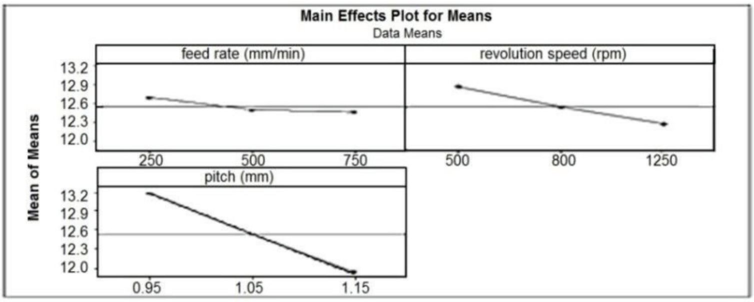

Figure 8: Main effects plot for means obtained from numerical approach

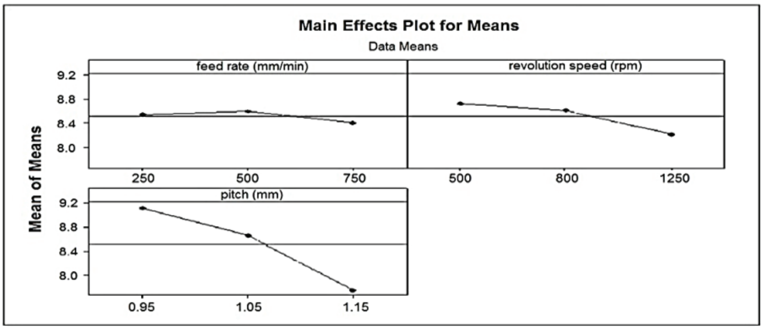

Figure 9: Main effects plot for means obtained from experimental approach

## 5.3 Results for method I

Figure 10 shows mean strain main effects plot for means. It depicted the best and the worst condition for factors z1, z2, z3 and z4. As smaller strain was preferred, for z1, vertical feed equal 0.9 mm yielded smaller mean strain and for the rest factors 1.1, 1.3 and 0.7 mm, respectively provided more desirable condition. Therefore, the optimum setup was (0.9 1.1 1.3 0.7).

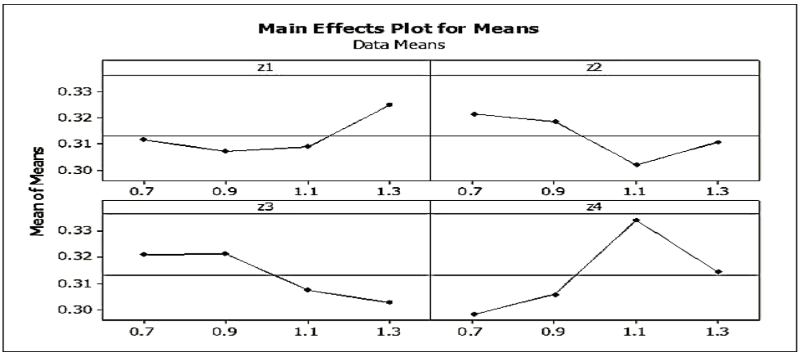

Figure 10: Mean strain main effects plot for means

## 5.4 Results for method II

To determine the best FPA value to minimize the strain deference, the initial value for wall angle was assumed to be 65° and the experiments were designed around this angle. With an aid of numerical simulation, the equivalent plastic strain on the pyramid corner was determined and strain differences were calculated for various FPAs (Table 9).

Table 9: Strain differences for various FPAs (numerical approach)

| FPA (degree) | 58 | 59 | 60 | 61 | 62 | 63 | 64 |
|---|---|---|---|---|---|---|---|
| Strain difference (max-min) | 0.09354 | 0.0576 | 0.03014 | 0.0026 | 0.00385 | 0.01093 | 0.08855 |
| FPA (degree) | 65 | 66 | 67 | 68 | 69 | 70 | 71 |
| Strain difference (max-min) | 0.1115 | 0.09065 | 0.0207 | 0.0412 | 0.02742 | 0.08006 | 0.06627 |

In order to find the minimum point, a quadratic equation was fitted through points in a reasonable interval [$58^\circ$ to $65^\circ$] around minimum point.

$$\text{Strain Difference} = 0.0085(\text{FPA})^2 - 1.0413(\text{FPA}) + 31.944 \qquad (1)$$

Applying derivation on trend line equation, the minimum point can be concluded as FPA = $61.25^\circ$.

## 6.0 CONCLUSION

A three-dimensional finite element simulation through ABAQUS is employed to investigate the effects of influential parameters on the formability of Aluminum sheet in single-point incremental forming process. Experiments have been carried out to verify the validity of numerical results. Comparison of experimental and numerical results showed a considerable agreement. Taguchi method is applied to optimize the effective parameters for the single point incremental forming process. The optimum forming condition, which is the feed rate of 250 mm/min, the revolution speed of 500 rev/min and the pitch of 0.95 mm are obtained for the best response values. Step pitch variation affects the formability dramatically and with small decrease in step pitch value, formability increases considerably. However, parameters like feed rate and punch revolution speed have small effects on formability. Two methods are presented to enhance the formability. In the first method, pitch values are distributed around its ordinary vertical feed. The best values for variable step pitches are determined. In the second method, forming path angle (FPA) has been presented in order to find the most normalized strain distribution. The optimum forming path angle is determined as $61.25^\circ$.

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