Effects of Process Parameters in Incremental Sheet Metal Forming Using Visioplasticity Method

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Received on: 7/9/2015 & Accepted on:21/4/201٦

ABSTRACT

Single point incremental forming SPIF is a flexible manufacturing process that does not require a special die for each part and is conducted on CNC milling machine that control on the motion of the forming tool. The formability is very important in any forming process therefore this work is concentrated on the influence of some factors on formability during SPIF. The factors that were studied are: type of tool path, depth step, feed rate and tool rotational speed. Three factors (depth step, feed rate and tool rotational speed) are examined depending on three levels (low, medium and high levels) while the type of the tool path was examined depending on two levels (low and high levels). In this work the total number of experiments is 18 experiments except the screening experiments that were made before the main experimental tests. Response surface method is used to build the predictive model to predict the value of effective strain for experiments that are not experimentally conducted. The results show that the feed rate and interaction between step size and type of tool path have the largest effect on formability. It is found that the maximum value of formability in terms of effective strain was ($\bar{\varepsilon} = 0.5049$) while the minimum value was ($\bar{\varepsilon} = 0.26456$). It is also found that SPIF is affected by the friction at the interface between forming tool and sheet metal as in other metal forming processes.

Keyword: Formability, Incremental Sheet Metal Forming Process, Effective Strain.

INTRODUCTION

The technology of sheet metal forming (SMF) has a very high importance in manufacturing and can be defined as the ability of metal to deform plastically or changing the shape of the sheet into a new desirable shape without necking or crack [1]. During the past few years there has been increasing demand for the need of development of manufacturing technologies that are both agile and be able to handle with the market requirements, that is it should be also adaptable for new product development so that introduction of new products in the markets could be easily achieved. Traditional SMF requires expensive various dies, which includes dedicated dies, positive and negative dies etc. Besides the expensive cost, it also lacks flexibility to meet the demand of customer for the traditional processing [2] . To meet increasing demands for customized and new products of various shapes and materials, production in small quantities at low cost, etc., a few flexible, innovative, and rapid manufacturing methods have been introduced recently. One of these methods is single point incremental forming SPIF [3]. This process can be used for forming of symmetric and non-symmetric parts in a wide range of thicknesses from 100 microns up to several mm [4].

https://doi.org/10.30684/etj.34.12A.15
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Literature Survey

Researches Regarding the Formability and Strains in Incremental Sheet Metal Forming ISMF Process

Some researches define the formability during ISMF in terms of the maximum forming angle. The maximum angle (Ø max) is the greatest angle formed in a shape without any failures [5]. The wall angle is measured in terms of a tangent line from the unformed sheet surface to the deformed surface. One method for easily determining the maximum permissible wall angle is the Variable Wall angle Conical Frustum (VWACF) test. This test which was proposed by Hussain and Gao [6] , tests the thinning limits of parts by forming a shape with increasing wall angle with depth. The part is formed until fracture occurs within the wall, and based on the depth of fracture the angle can be calculated from the CAD model [6]. With the maximum wall angle it is difficult to characterize the complex strain state and formability behavior in incremental sheet metal forming. 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 [7]. Although other researchers define the formability depending on other criteria such as maximum thinning but the maximum wall angle is the most used criterion to express the material formability limit in the case of incremental sheet metal forming process.

In this work the formability is defined in terms of effective strain.

Rattanachan K. (2009) [8] studied the effect of tool effective speed (spindle speed and feed rate) on the formability during single point incremental sheet metal forming. The result shows, that the spindle speed and the feed rate affect SPIF formability of sheet metal. **Adrian Blaga (2012)** [9] studied by optical methods the effect of geometrical parameters on the principal strains and the thickness reduction in the SPIF process for two types of components a straight groove and a dome part. The parameters which were taken into account are the punch diameter and step size. Tests were done on two thicknesses of the same material but having different mechanical characteristics. **Fabio Andre Lora (2014)** [10] studied the effect of step size and punch diameter on major and minor strain in incremental sheet metal forming process. All experiments were conducted on a DC04 sheet blank with thickness 1 mm and the test specimen was a simple straight line geometry. It is found that the strains in the incremental forming process are much higher than those of the conventional processes. **K. Rattanachan (2014)** [11] compares formability of SS 400 steel and SUS 304 stainless steel in SPIF. The two materials were formed into cone shape specimens with different wall's incline angles: 90° , 75° and 60°. The experimental result shows that the smaller the wall incline angle the higher the formability with the both materials. It is found that SS 400 has higher formability than SUS 304.

Theoretical Considerations

In the current part theoretical models concerning strains and stresses are considered. These cases are issues that have big practical importance.

Plasticity Relations

It is assumed that $\sigma_3 = 0$ (plane stress condition).

Von Mises yield function can be defined as [12] :

$$\bar{\sigma} = \sqrt{\sigma_1{}^2 + \sigma_2{}^2 - \sigma_1\,\sigma_2} \qquad \dots(1)$$

The ratio of the minor stress to the major stress is defined by the parameter:

$$\alpha = \frac{\sigma_2}{\sigma_1} \qquad \dots(2)$$

Where: α is the stress ratio.

Similarly, the ratio of the minor strain to the major strain is defined by the parameter:

$$\beta = \frac{\varepsilon_2}{\varepsilon_1} \quad \ldots(3)$$

Where: β is the strain ratio.

By rearranging equations (1) and (2), effective stress ($\bar{\sigma}$) can be written as :

$$\bar{\sigma} = \sqrt{{\sigma_1}^2 + {\sigma_1}^2\alpha^2 - \sigma_1\,\sigma_1\,\alpha}$$

$$\bar{\sigma} = \sqrt{{\sigma_1}^2 + {\sigma_1}^2\alpha^2 - {\sigma_1}^2\,\alpha}$$

$$\bar{\sigma} = \sqrt{{\sigma_1}^2\,(1 + \alpha^2 - \alpha)}$$

$$\bar{\sigma} = \sqrt{1 - \alpha + \alpha^2}\,\sigma_1 \quad \ldots 4$$

The relation between the stress and strain ratios can be expressed as [13] :

$$\alpha = \frac{2\beta + 1}{2 + \beta} \quad \ldots 5$$

$$\beta = \frac{2\alpha - 1}{2 - \alpha} \quad \ldots 6$$

The effective strain is given by the von Mises yielding criterion and can be determined by these equations:

$$\bar{\varepsilon} = \sqrt{\frac{2}{3}({\varepsilon_1}^2 + {\varepsilon_2}^2 + {\varepsilon_3}^2)} \quad \ldots 7$$

$$\bar{\varepsilon} = \sqrt{\frac{4}{3}(1 + \beta + \beta^2)}\;\varepsilon_1 \quad \ldots 8$$

The most commonly used representation of stress– strain relation is the power law

$$\bar{\sigma} = k\bar{\varepsilon}^n \quad \ldots 9$$

The average of the principal stresses represents the hydrostatic stress and is calculated from:

$$\sigma_h = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

In the case of plane stress condition the equation above become:

$$\sigma_h = \frac{\sigma_1 + \sigma_2}{3} \quad \ldots 10$$

The major strain is calculated using this equation:

$$\varepsilon_1 = ln\frac{l}{lo} \quad \ldots 11$$

The minor strain is determined by this equation:

$$\varepsilon_2 = ln\frac{w}{wo} \quad \ldots 12$$

The thickness strain could be found by applying the value of major strain (Eq 11) and minor strain (Eq 12) to the incompressibility equation (Eq 14) and is equal to :

$$\varepsilon_3 = ln\frac{t}{to} \quad \ldots 13$$

The incompressibility equation is given by:

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \quad \ldots 14$$

Experimental Work

ISMF process is characterized by using very simple equipment in addition to utilized CNC milling machine compared with other SMF operations that utilized punches and dies specific to the one geometry and size of the final part [14]. The tests were conducted to measure the strains during ISMF process and determine the effects of process parameters (spindle speed, feed rate, step size and tool path) on the formability of a cone geometry. The test set-up and the experimental techniques will be presented in this part.

CNC Milling Machine Used in This Work

ISMF is usually performed on several machines such as CNC milling machine, CNC lathe machine that control on the movement of the forming tool during forming process. In this work, the experiments were conducted using three-axis vertical milling machine “C-tek” model “KM-80D” 2008 to manufacture the required products. Figure (1), demonstrates the CNC milling machine used in the experimental work.

Figure (1) : CNC milling machine used in the experimental work

Forming Frame and Blank Holder

The hollow cylindrical frame is manufactured from medium carbon steel by turning machine with outer diameter (220 mm) and inner diameter (190 mm) and height of (200mm). A ring with radii equals to the radii of the forming frame has been used as a blank holder. As shown in figure (2), the blank holder has nine holes distributed uniformly along the circumference of the frame and the blank holder. Nine studs (M8) are utilized in order to fix the blank between the frame and the blank holder. The forming frame is fixed on the table of CNC milling machine by using a suitable clamp.

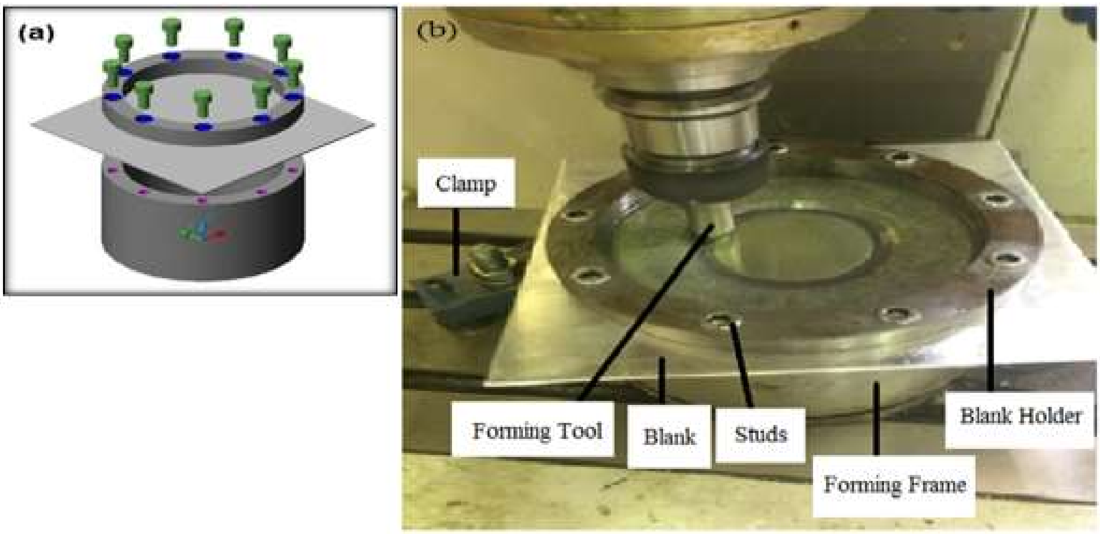

Figure (2) : The forming structure used for experiments, (a) graphical representation and (b) physical frame representation

Forming Tool

The main function of the forming tool in ISMF is to create a zone of highly localized stresses on the surface of the metal and thus manufacture the required parts by localized plastic deformation. In this work the hemispherical head forming tool is used to perform all of the manufacturing operations according as shown in Figure (3).

Figure (3) : Forming tool used in experimental work

The tool having circular cross-section and a hemispherical tip with diameter of 23mm and length of 100 mm. The hemispherical head of the forming tool was coated by chromium in order to reduce the friction among tool and metal.

Material Type and Selection

In this work the material selected is aluminum 1050 H14 with initial size is 240×240×0.9 mm depending on the diameter of the frame for making component of required shape as shown in fig (4). The sheet is marked with the grid before forming process is carried out. After forming spray paint of silver color was sprayed on parts in order to fix the ink and to prevent any wipe that may occur before measurement process.

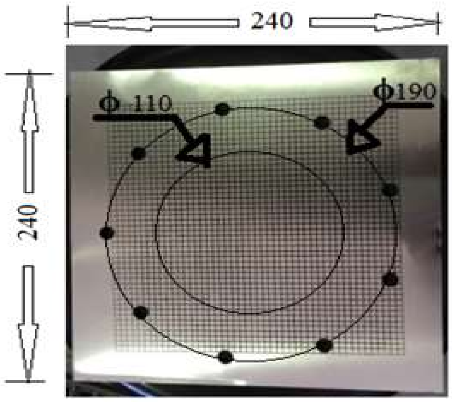

Figure (4) : Aluminum 1050 H14 sheet with 4 × 4 mm square grid.

Programming Procedure for SPIF

Solidwork Geometry Design

The cone geometry was designed by Solidworks program as shown in figure (5). This geometry has a depth of 28 mm, with the top radius of 55 mm and bottom radius of 22 mm and wall angle equal to 40°. The part must be in a shape of cubic or cylinder not a sheet metal shape to implement a tool path on Surfcam and UG-NX9 programs because these programs don't have incremental forming feature. Solidworks part needs to be saved in sldprt file type to be used with Surfcam and UG-NX9 programs.

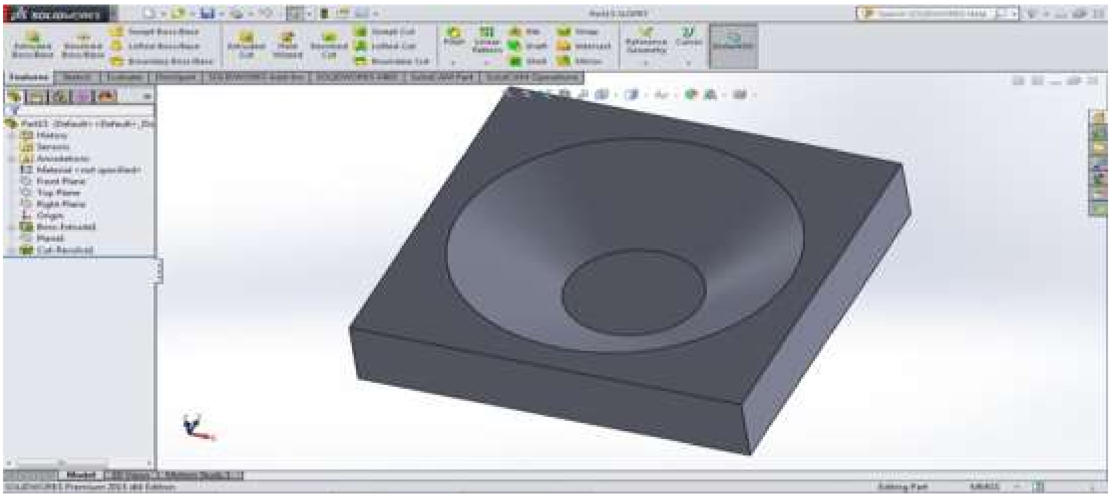
Figure (5) : Cone geometry design by solidworks program.

CAD/CAM Program

There are two types of tool path used in this work spiral path and z-level path. The spiral path is shown in figure (6) while the z-level path is shown in figure (7).

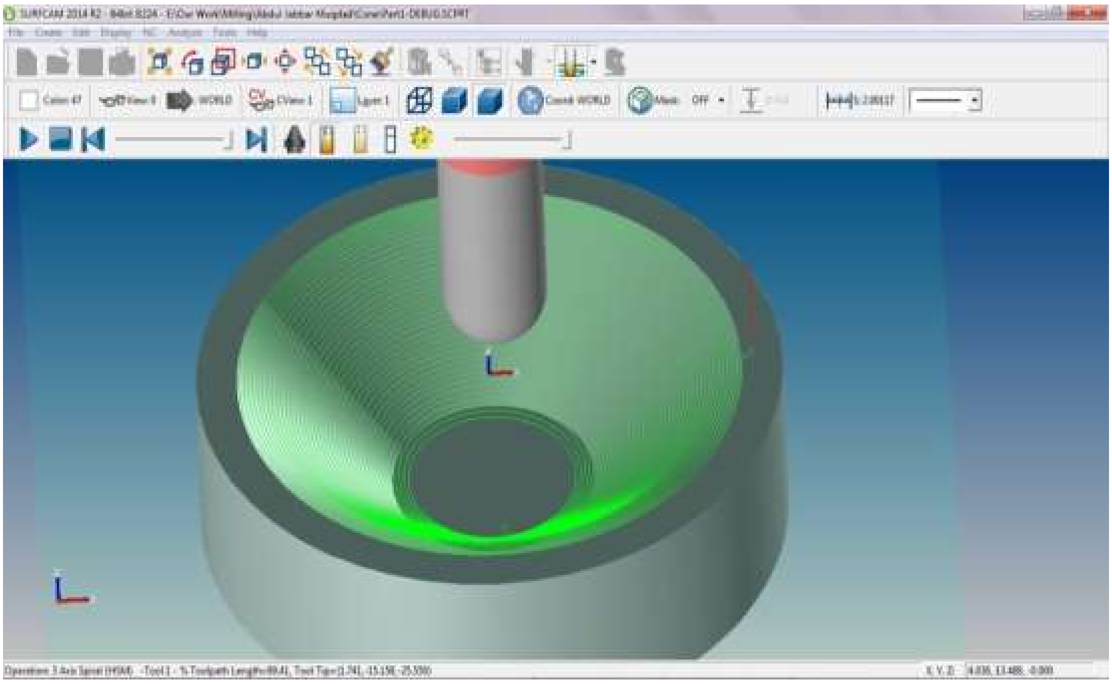
Figure (6) : Spiral path for cone geometry

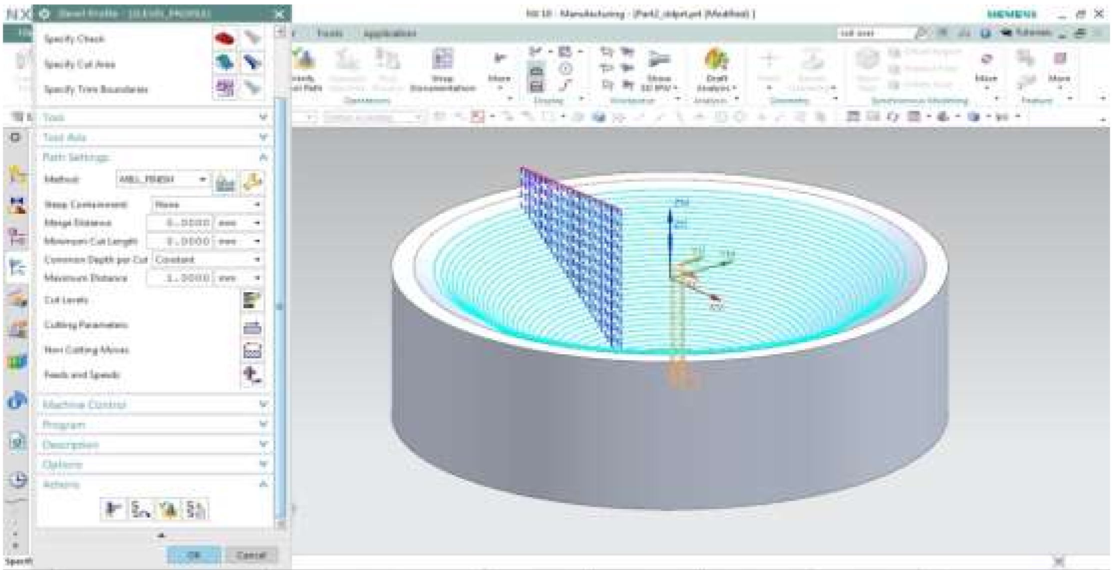

Figure (7) : Z-level path for cone geometry

The spiral tool path was generated by Surfcam program while z-level tool path was generated by UG-NX9 program. In order to generate both of spiral and z-level tool paths, the Sldprts files of Solidworks geometries must be uploaded to Surfcam and UG-NX9 programs. The selection of Surfcam and UG-NX9 programs among very many CAM programs because of integrated with Solidworks program used for designing the part.

The tool path is generated after the selection of the surface area and entering all the information associated with the operation such as the value of step size.

After simulation of the tool path has been performed, the program code will be supplied and saved as text file. The resulting NC file can be opened on Notepad program for code correction. Figure (8) shows all samples of cone geometry.

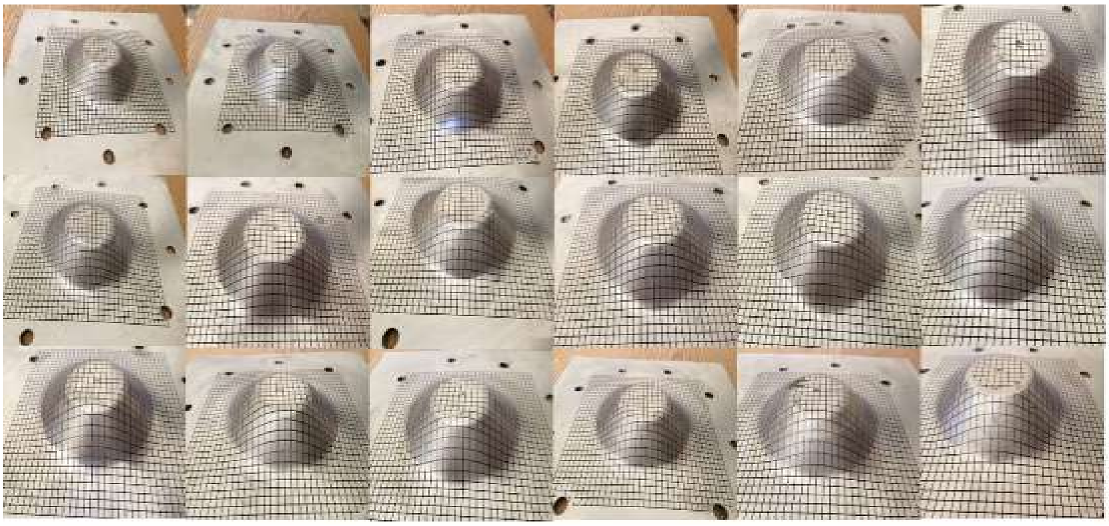

Figure (8) : All samples of cone geometry

Developing the Experimental Design Matrix

Design of experiment DOE is a systematic method to determine the relationship between factors affecting a process and the output of that process. In design of experiment DOE all possible combinations can be investigated (full factorial) or only a portion of the possible combinations (fractional factorial) [15]. In this work Taguchi fractional factorial experimental designs that use a very limited number of experimental runs is used.

This method reduces the number of experiments from 54 experiment to 18 experiment as given in table (1). The original values of the factors are coded as -1, 0, 1 for low, medium and high level respectively.

Table (1) : Experimental design matrix according to Taguchi method

Expt. No.	Coded Value				Original Value			
	c	f	hz	q	c	f	hz	q
1	-1	-1	-1	1	500	700	0.4	spiral
2	-1	0	0	1	500	1400	0.8	spiral
3	-1	1	1	1	500	2100	1.2	spiral
4	0	-1	-1	1	1500	700	0.4	spiral
5	0	0	0	1	1500	1400	0.8	spiral
6	0	1	1	1	1500	2100	1.2	spiral
7	1	-1	0	1	2500	700	0.8	spiral
8	1	0	1	1	2500	1400	1.2	spiral
9	1	1	-1	1	2500	2100	0.4	spiral
10	-1	-1	1	-1	500	700	1.2	z-level
11	-1	0	-1	-1	500	1400	0.4	z-level
12	-1	1	0	-1	500	2100	0.8	z-level
13	0	-1	0	-1	1500	700	0.8	z-level
14	0	0	1	-1	1500	1400	1.2	z-level
15	0	1	-1	-1	1500	2100	0.4	z-level
16	1	-1	1	-1	2500	700	1.2	z-level
17	1	0	-1	-1	2500	1400	0.4	z-level
18	1	1	0	-1	2500	2100	0.8	z-level

Results and Discussion

General Results

This part will give some of the results obtained from cone shape that is utilizing the for mentioned C-tek 3-axes CNC milling machine. Table (2) will give the results of sample 15 of cone geometry using straight path of measurement. The first step for calculation these results is measure the dimension of the grid by microscope and after that it is possible to determine other results. In order to understand the mechanism of deformation in the process, principal strains are measured at four regions and two paths. These regions are: top radius zone, cup wall zone, bottom radius zone, cup bottom zone and the paths are: straight and oblique.

Table (2) : Results of sample 15 of a cone geometry by straight path of measurement

output	Top radius zone	Cup wall zone	Bottom radius zone	Cup bottom zone
l (mm)	4.66	5.53	4.32	4
ε_1	0.15272	0.32389	0.07696	0
w (mm)	4.3	4.37	4.012	4
ε_2	0.07232	0.08846	0.00299	0
ε_3	-0.22504	-0.41235	-0.07995	0
t (mm)	0.71863	0.59588	0.83084	0.9
r	20.15222%	33.79111%	7.68444%	0%
β	0.47354	0.27311	0.03885	
α	0.78716	0.68022	0.52858	
$\bar{\varepsilon}$	0.22977	0.43417	0.09064	0
$\bar{\sigma}$ (Mpa)	83.0815	97.4083	65.8432	0
σ_1 (Mpa)	91.0589	110.1183	75.9878	0
σ_2 (Mpa)	71.6779	74.9046	40.1656	0
σ_h (Mpa)	54.2456	61.6743	38.7178	0

Quantitative Analysis

Main Effect Plot (MEP)

Figure (9) shows the main effects of the four controlling factors for the average $\bar{\varepsilon}$ that is used in this work.

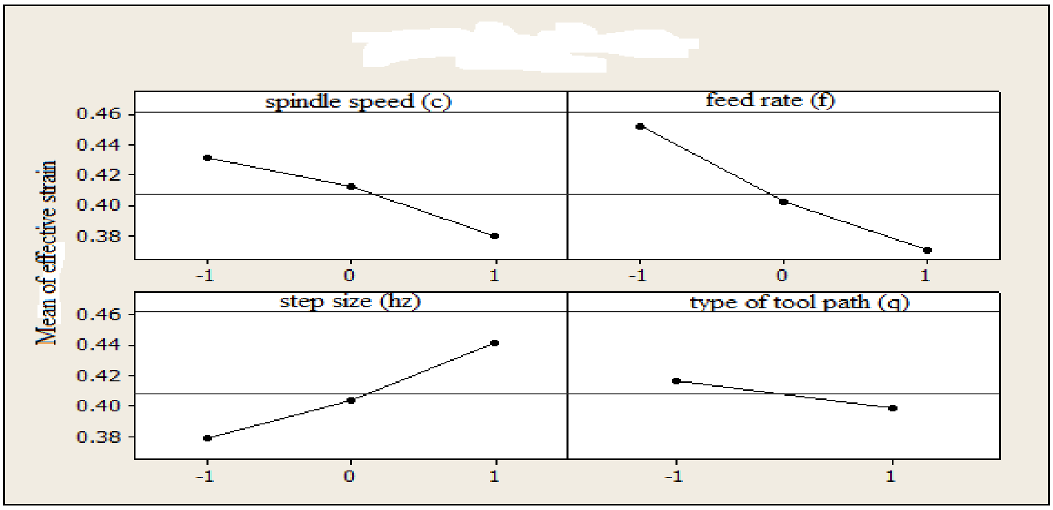

Figure (9) : Main Effect Plot for $\bar{\varepsilon}$

MEP indicates that the response ($\bar{\varepsilon}$) decreases as the factors (c, f, and q) move from their low to high levels, while an increase in this response is observed when the factor (hz) moves from its low to high level.

Prediction of Effective Strain

The response surface method is used here to generate a predictive model between the effective strain and the control factors. The response surface method is a part of statistics that deals with the investigation of the relationship between the control factors and their interactions and the required response. The determination coefficient R^2 and the correlation coefficient (rc) are used to judge about the robustness and appropriateness of the predictive model. The predictive model divides into three distinctive models according to the ranges of the correlation coefficient [16] :

$0 \leq \lvert rc \rvert \geq 0.5$	weak model
$0.8 \leq \lvert rc \rvert \leq 1$	strong model
Otherwise	moderate model

In this model the maximum absolute error is within 93% level of confidence and the value of correlation coefficient is equal to 0.99871 therefore this model is considered as strong model. The predictive model is generated using minitab 16 statistical software and is given by:

$$\bar{\varepsilon}p = 0.402504 - 0.025783c - 0.040805f + 0.031389hz - 0.009058q - 0.007084c^2 + 0.009002f^2 + 0.00604hz^2 - 0.000774cf - 0.000378chz - 0.021336cq - 0.041821fhz - 0.013521fq + 0.034926hzq \qquad 15$$

Where: c is spindle speed, f is feed rate, hz is depth step and q is type of tool path.

Analysis of Variance (ANOVA)

Although the main effect plot explores the effect of each control factor but it has the disadvantage of not providing an explanation about the interaction effect between parameters and which of these parameters are significant. The current study is controlled by four control factors and six interactions; therefore, there would be ten sources of variation control the required effective strain. So ANOVA has a sharp criterion to explore the interaction effect and to select the significant parameter or interaction from ten sources by analyzing the significant effect through F- Fisher test or probability value P- value. This analysis is carried out for the level of confidence of (β_1=95%), therefore the level of significance is (β_2=5%). Thus the source of variation is considered to be significant if its P-value ≤ 0.05. ANOVA is only suitable for full factorial experimental designs. Therefore the 18 experiment is modified to full factorial design of 54 trails based on virtual experiments by using predictive model represented by equation (15). The ANOVA table that is shown in table (3) is created using MATLAB function "anovan" .

Table (3) : ANOVA results test for effective strain

Source	Sum sq.	d.f.	Mean sq.	F	Prob > F
c	0.02453	2	0.01227	45.32*	0*
f	0.06092	2	0.03046	112.52*	0*
hz	0.03591	2	0.01795	66.33*	0*
q	0.00443	1	0.00443	16.37*	0.0004*
cf	0.00128	4	0.00032	1.19	0.3386
chz	0.0014	4	0.00035	1.29	0.2978
cq	0.01771	2	0.00886	32.72*	0*
fhz	0.04283	4	0.01071	39.56*	0*
fq	0.00663	2	0.00332	12.25*	0.0002*
hzq	0.04394	2	0.02197	81.16*	0*
Error	0.0758	28	0.00027		
Total	0.24716	53			

The source of variation is considered significant if it satisfies the condition in Equation (16) :

$$F \geq F_T(\beta_2, v_d, v_r) \qquad \ldots \quad 16$$

Where

F is the calculated F-ratio of a given source of variation as illustrated in table (3), F_T is the tabulated F-ratio, β_2 is the level of significance used in the test (β_2=0.05), v_d is the degree of freedom of given sources (v_d = 1, 2,4) and v_r is the degrees of freedom error (v_r = 28). The tabulated F_T ratios for all factors and interactions that based on 5% level of significant and degree of freedom are [F_T(0.05, 1, 28) = 4.196] for (q) source, [F_T(0.05, 2, 28) = 3.3404] for (c, f, hz, cq, fq and hzq) sources and [F_T(0.05, 4, 28) = 2.7141] for (cf, chz and fhz) sources. Based on ANOVA table (table 4) and sorted from most to least significant, feed rate (f), interaction between step size and type of tool path (hz and q), step size (hz), spindle speed (c), interaction between feed rate and step size (f and hz), interaction between spindle speed and type of tool path (c and q), interaction between feed rate and type of tool path (f and q) and type of tool path (q) are considered to be significant factors of effective strain response because their F- ratios are more than the tabulated F_T- ratio and their P-values are less than 0.05 while the interaction between spindle speed and feed rate (c and f) and interaction between spindle speed and step size (c and hz) is not significant.

Qualitative Analysis of Formability

This section will provide a discussion of the results that have been obtained from the experimental work, which include controlling factors and their impact on the output (effective strain). The cup wall zone of a cone with straight path of measurement is selected in order to explain the effect of process parameters in this region. The reason for selecting this zone because the highest strains occur at this zone.

Analysis of Experimental Results

In this work the measures of all experiments have been divided into five groups depending on the values of the effective strain ($\bar{\varepsilon}$) in order to simplify the analysis and discussion of formability in single point incremental forming process.

These groups are:

1- The first group includes the experiments (Expt. No. 5, 10 and 16) with a range of ($\bar{\varepsilon}$ = 0.5049- 0.47186). The combination of factors for this group is low and medium levels of feed rate (f = 700 and 1400 mm/minute), medium and high levels of step size (hz = 0.8 and 1.2 mm), z-level tool path except the experiment (Expt. No. 5) and three values of spindle speed (c = 500, 1500 and 2500 r.p.m). This group contains the best or the optimal experiment (Expt. No. 10) in terms of formability which has the maximum effective strain ($\bar{\varepsilon} = 0.5049$).

2- The second group includes the range of effective strain ($\bar{\varepsilon} = 0.43463$- 0.42253) and has the experiments (Expt. No. 3, 11, 13 and 15). The combination of parameters for this group is low and medium levels of spindle speed, z-level tool path except the experiment (Expt. No. 3) and three values of both feed rate and step size.

3- The third group contains the experiments (Expt. No. 1, 8 and 17) and a range of effective strain ($\bar{\varepsilon} = 0.41649 – 0.40261$). The engaged factors for this group are low and high levels of spindle speed and step size, two levels of feed rate (low and medium levels), spiral tool path for experiments (Expt. No. 1 and 8) and z-level tool path for experiment (Expt. No. 17).

4- The fourth group involves the experiments (Expt. No. 7, 12, 14 and 18) with a range of ($\bar{\varepsilon}$ = 0.39887- 0.38685). The combination of factors for this group is medium level of step size except the experiment (Expt. No. 14) that has a high level of a step size, z-level tool path for experiments (Expt. No. 12, 14 and 18) and spiral tool path for experiment (Expt. No. 7) in addition to three levels of both spindle speed and feed rate.

5- The fifth and last group includes ($\bar{\varepsilon}$ = 0.37608- 0.26456) with the experiments (Expt. No. 2, 4, 6 and 9). The conditions of these experiments are spiral tool path with three levels of spindle speed, feed rate and step size. This groups contains the experiment (Expt. No. 9) that has a minimum formability ($\bar{\varepsilon}$ = 0.26456).

From these results and through MEP (Figure (9)), it is observed that when the spindle speed increase the formability will decrease due to increased the friction at tool sheet interface. At lower values of spindle speed the forming tool will roll over the sheet metal surface (the friction is rolling friction) and in this case the friction is low. At higher values of spindle speed the forming tool will slide along sheet metal surface (the friction is sliding friction). This increased the friction at tool sheet interface and will and this is clear from changing the color of the lubricant into black color .The friction has negative effect on formability because when the friction increased higher energy is required to overcome the friction therefore the activation energy required to activate the dislocations motion will decreased and this leads to curb or impede the movement of dislocations and the formability decreases in this case and this agrees with the researcher Rattanachan K. [8]. It is found when the feed rate increases the formability will decrease. Larger feed rate increased the strain rate and reduced the probability of emission of local heating. In this case the phenomenon of the recrystallization is not occur. Therefore the formability will increase if lower value of feed rate is used but at the same time this will increase the manufacturing time and this agrees with the researchers M. Ham & J. Jeswiet [4], Rattanachan K. [8]. The effective strain is decreased when spiral tool path is used. In spiral tool path all three axes move at the same time therefore the process is continuously from start to end without repeated penetrations of the forming tool in z direction while in z-level tool path two axes (x and y axes) were traveled together to make circular movement that start at the same point and after the completion of this movement the forming tool will penetrate in z direction. Therefore the forces in z-level tool path are more than the forces in spiral tool path and this leads to higher stresses that causes larger strains in z-level tool path compared with spiral tool path. The effective strain is increased when larger values of step size are used and this does not agree with the researchers M. Ham & J. Jeswiet [5] and Fabio Andre Lora [10] because the forces are increased and the resultant are larger stresses in the case of higher values of step size.

CONCLUSIONS

The main conclusions of this work are:

1- The distribution of strain in cone shape during single point incremental forming depends on the action of the forming tool.

2- It is found that the hydrostatic pressure has an important part in incremental sheet metal forming process because each increase in effective strain is escorted with an increase in hydrostatic pressure.

3- The maximum values of principal stresses occur at cup wall zone because the amount of the applied load has maximum value at this zone.

4- It was found that the effect of bending be confined only at top radius zone because the yielding started at this zone therefore the energy required to make the elastic deformation is equal or a little less to the energy required to make the plastic deformation.

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