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# Investigation the Effect of Process Variables on the Formability of Parts Processed by Single Point Incremental Forming

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## Abstract

Incremental sheet metal forming process is an advanced flexible manufacturing process to produce various 3D products without using dedicated tool as in conventional metal forming. There are a lot of process parameters that have effect on this process, studying the effect of some parameters on the strain distributions of the product over the length of deformation is the aim of this study.

In order to achieve this goal, three factors (tool forming shape, feed rate and incremental step size) are examined depending on three levels on the strain distributions over the wall of the product. Strain measurement was accomplished by using image processing technique using MATALB program. The significance of the control factors are explored using two statistical methods: analysis of variance (ANOVA) and main effect plot (MEP). All experiments were carried out on a sheet of Aluminum alloy (Al1050) with thickness 0.9 mm by using 3 axes CNC machine to produce frustum pyramid product. The result showed that the feed rate is a parameter that has large effect on the values of the effective strain percentage contribution of (42.86% and 51.42%), respectively, and is followed by step size (25.1% and 30.60%) percentage contributions and finally the tool shape with (21.79% and 10.54%) on the (55° and 45°) wall angle, respectively. The maximum and minimum average effective strain computed on the 55◦ forming angle were (0.580 and 0.399), respectively. Finally, the maximum and minimum average effective strain computed on the 45◦ forming angle were equal to (0.412 and 0.324), respectively.

***Keywords*****:** *Effective strain, Forming limit diagram, Incremental sheet forming.*

## 1. Introduction

Single point incremental forming (SPIF) is a very simple, flexible and cost-saving alternative to the classical forming processes of metal sheets when low volume batches, customized parts or prototypes have to be manufactured. This technology does not require dedicated expensive tools. On the contrary, the metal sheets, tightly held at the periphery by a frame situated on the worktable of a CNC milling machine, is formed by a rigid tool programmed to follow, usually, a succession of planar contours or a single spiral contour. Incremental sheet metal forming is a modern method, which brings new possibilities of sheet metal forming. Nowadays a lot of attention is focused on the single point incremental sheet metal forming, where the dedicated die is not needed. This method has a large number of adaptable process parameters influencing the forming results. The process parameters that are usually of interest in SPIF are: thickness of the sheet, size of the vertical step down (Δz), tool size, tool speed (spindle speed and feed rate), lubrication and material properties [1,2, 3]. When reviewing previous literatures with regard to incremental sheet metal forming process reveal that ISF method is well investigation, but there are still some issues not well understood in incremental forming like strain distribution on the sheet over the length of deformation, therefore author focused on this field. Khamis E. A. Essa

[4] investigated the deformation mechanics of single point incremental forming by constructing a novel dual level FE model of the forming of a truncated cone. The first-level FE model is validated against experimental data and is used to explore the principal characteristics of the deformation, geometries of the final part, and the normal strains. The second level finite element model is used to investigate the deformation modes through the sheet thickness. The effect of the through-thickness shear strain on the formability is show by using a Marciniak-Kuczynski model. Design of experiment and analyses of variance techniques are used to study the effect of the various process variables on the predicted through-thickness shear. Simple strategies that include modification of tool path, adding a backing plate, using a kinematic supporting tool are applied to reduce the geometrical errors without affecting the process flexibility. The results of the second-level finite element model indicated that shear, both parallel to and perpendicular to, the tool plane is a significant component in the deformation mechanism in single point incremental forming and that it has an important influence on increasing the necking limit and hence improving formability. The applied strategies result in a significant reduction in the errors in the geometrical, enhancing the possibility of using the process in critical applications.

Investigation the effects of process variables during single point incremental sheet metal forming on formability of 1050 H14 Aluminum alloy is concentrated by K. M. Younis and A. M. Abdul Jabar [5] and also focused on construction the forming limit diagram, fracture forming line and forming limit stress diagram depending on results from tensile and bulge tests to find out the safe and failure zones of Al1050 alloy. The variables were studied are : type of tool path, rotational speed, feed rate and depth step are examined depending on three level ( low, medium, high) to produce cone and half sphere shapes. Compare strain and thickness distributions between two shapes were made. The result show that the feed rate and interaction between depth step and type of tool path have the largest effect on the formability in term of effective strain. Muhaned F. Nory [6] implemented and designed the incremental forming process for multilayer sheets of aluminum. In this work author studies the effect of the use multilayer sheet on the texture and tool path marks. Aw well as, investigated the effect of two control factors (thickness of the top plate, lubrication or material used between tow plates) on the residual stresses and hardness on the surfaces of the top and bottom plates produced in this process. It is founded use of multilayer instead of single layer decreases the poor texture and too path marks and the change in the thickness of top plate has a greatest effect on the tool path marks, residual stresses and hardness on the top and bottom plates produces by multilayer incremental forming then change in lubrication and material between plates. Finally, using (Ansys) software based on finite element method to predict the strain distributions on the multilayer incremental forming process.

## 2. Experimental Procedures

### 2.1 Introduction

The experimental works mainly include four sections; the first one is the section of the type of the material sheet and construction of the forming limit diagram of the sheet selected by preparing and performing tensile and bulge tests necessary for this diagram. The second section is building and preparation of some equipments and tools necessary for single point incremental forming experiments then the third section includes all methods and programs used for measuring of the strain distributions over the products. Finally the last section is investigation of the effect of process factors by using statistical methods.

### 2.2 Material Type

The type of the material selected in this study is an aluminum sheet (Al1050) with initial thickness 0.9mm. the chemical composition of the sheet is listed in table 1. The chemical composition studied in State Company for Inspection and engineering Rehabilitation activities (S.I.E.R).

**Table 1,**
**Chemical composition of the aluminum sheet (Al1050) (% of mass).**

| Element | Al | Fe | Si | Mg | Mn | Cu | Ti | V | Zn |
|---|---|---|---|---|---|---|---|---|---|
| Com. | 99.5 | 0.32 | 0.091 | 0.025 | 0.021 | 0.015 | 0.011 | 0.01 | 0.007 |
| Iso | ≥99.5 | ≤0.4 | ≤0.25 | ≤0.05 | ≤0.05 | ≤0.05 | ≤0.05 | ≤0.05 | ≤0.07 |

## 2.3 Forming Limit Diagram

The deformation of the sheet metal is limited to a certain level imposed by the occurrence of necking or fracture. The best way to describe this level is the forming limit diagram, therefore the formability of the sheet metals can be characterized using forming limit diagram (FLD), which is a plot reflects the maximum principal strains that can be sustained by sheet metal prior to the onset of localized necking [7]. In order to construction of the forming limit diagram for the sheet used in this study (Al1050) aluminum alloy this required determine the values of principal strains at three conditions: uniaxial tension, plane strain and equal biaxial tension conditions and connecting these values of strains by line. For determining the principal strain values in the uniaxial tension state the tensile test is used, while the strain hardening exponent represents the major strain the plane strain condition, finally the principal strain values in the equal biaxial tension condition are determined by bulge test.

### 2.3.1 Tensile Test

In this study the tensile test was performed for two reasons, the first reason is determining some of the important mechanical properties of the sheet due to the properties of the sheet used play insignificant role in the success of the forming process. while the second reason is determining the principal strains which used to build the left side from the forming limit diagram. The procedures used to get on the required results from the tensile test can summarized as follows. machined the tensile specimens from the sheet of (Al1050) Aluminum alloy with 90° to the rolling direction because this direction has the minimum values of the strength. The specimens were cut by a CNC milling machine from the material sheet according to ASTM standard, the dimensions of the specimen is shown in figure (1).

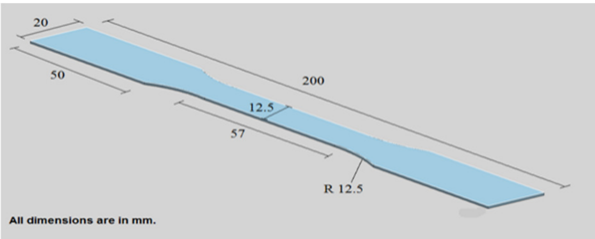



**Fig. 1. Dimensions of the tensile test specimen according to ASTM standard and E8M specification**

In order to measure principal strains, the specimen is printed with square grid with dimensions (4mmX4mm) by using screen printing method before test, then fixed the specimen by the gripers of the university testing machine model (WDW-200E) with a capacity 200KN and after that applied the tension load by the tensile machine on the specimen, it was elongated unit to fracture. author can get the load-deformation curve and the engineering stress and strain curve directly from the tensile test machine, but the information from last curve don't give good indicator for the properties of the metal through the forming process because of this curve depending on the original dimensions of specimen during test and don't take the changes in dimensions occurred, therefore we converted this curve to the true stress and true strain curve by using the equation (1,2) and from this curve author determine some of the important mechanical properties. The true stress and true strain curve are shown in figure (2). In addition, author can determine the principle strains by using the equations (2) and (3) by measuring the dimensions of grid marked on the specimen in the near of the fracture region before and after test by using image processing method. The specimen with grid marked before and after test are shown in figure (3a-3b), it is noted occurred of small necking ( no obvious necking ) before fracture due to plasticity properties of this (1050Al) alloy.

$$\sigma = \sigma^{\circ}\,(1+e) \qquad \ldots(1)$$

$$\in 1 = \ln\left(\frac{l}{l^{\circ}}\right) \qquad \ldots(2)$$

$$\in 2 = \ln\left(\frac{w}{w^{\circ}}\right) \qquad \ldots(3)$$

Where $\sigma$ = true stress, $\sigma^{\circ}$ = engineering stress, $\in$ = true strain, e = engineering strain, $\frac{l}{l^{\circ}}$ = ratio between instantaneous length and original length of the gauge section of the tension test specimen, $\in 1$= major strain, $\in 2$ = minor strain, $\frac{w}{w^{\circ}}$ = ratio between instantaneous width and original width of the gauge section of the tension test specimen. The mechanical properties and values of principal strains obtained from tensile test is shown in table 2.

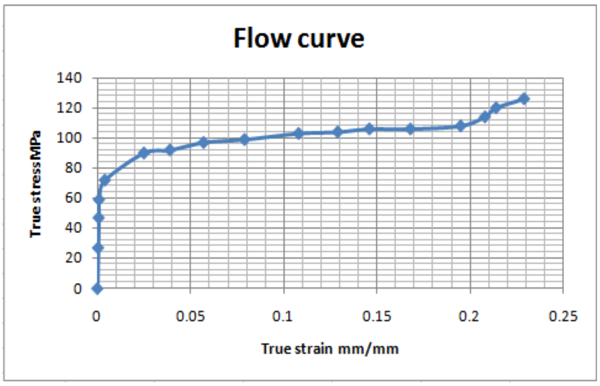



**Fig. 2. True stress and true strain curve.**

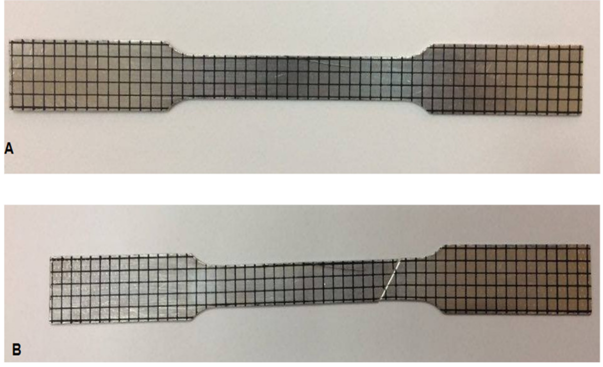



**Fig. 3. Specimen with grid, A. before tensile test, B. after tensile test**

**Table 2,**
**Mechanical properties and values of strains in the tensile test.**

| **Young modulus** | **Tensile strength** | **Offset yield stress** | **Strength coefficient** | **Strain hardening exponent** | $\epsilon_1$ | $\epsilon_2$ | $\epsilon_3$ |
|---|---|---|---|---|---|---|---|
| 70Gpa | 113Mpa | 93Mpa | 143Mpa | 0.19 | 0.07 | -0.032 | -0.047 |

## 2.3.2 Bulge test

The bulge test is a well described experimental set up for biaxial loading where stretch load is used to deform a specimen. Stretchability is the ability of the material to be stretched biaxially without failure. The Erichsen cupping test is a ductility test, which is employed to evaluate the ability of sheets material to undergo plastic deformation in stretch forming. This test can be classified as a stretch forming test which simulates plane stress in biaxial tensile deformation. A laboratory-scale stretch forming equipment has been designed and manufactured according to (DIN 50 101) for testing the stretchability of sheet material, it consists of four parts which have been manufactured from steel, and also have been machined on the lathe machine. These parts are the die, blank holder, punch and base. The die was designed with an inner diameter of 27 mm, entry radius 3 mm and an external diameter of 100 mm, for the purpose of centering with the blank holder, it has been made of diameter of 65 mm with depth of 11 mm cavity, and is has groove of draw bead at distance 40mm from the center of die. The blank holder has been designed to fix both the sample and a guide for the punch, where the internal diameter is 20.5mm and outer diameter is 100mm and height is 48mm, considering the die and the blank holder on the same center line, and it has circular draw bead at distance 40mm from centerline with radius equal to 0.5mm matching to the groove in the die, circular draw bead was located just after the corner radius of entrance of the die, which avoids drawing during the test. The punch was machined to obtain final diameter of 20 mm with hemispherical cavity at one end to fix the steel ball with 20 mm diameter in order to make spherical top for punch. The base was designed with an external diameter and a thickness of 130 x 22 mm respectively, making hole-center by drilling with a diameter of 21 mm to place the punch. A circular blank with a diameter of 65 mm was machined from the sheet and printed with square grid with dimension 4mm x 4mm by screen printing method, to fix undeformed blank between the die and the blank holder, six bolts (M6x1) were used. The stretch forming equipments are shown in the figure 4.

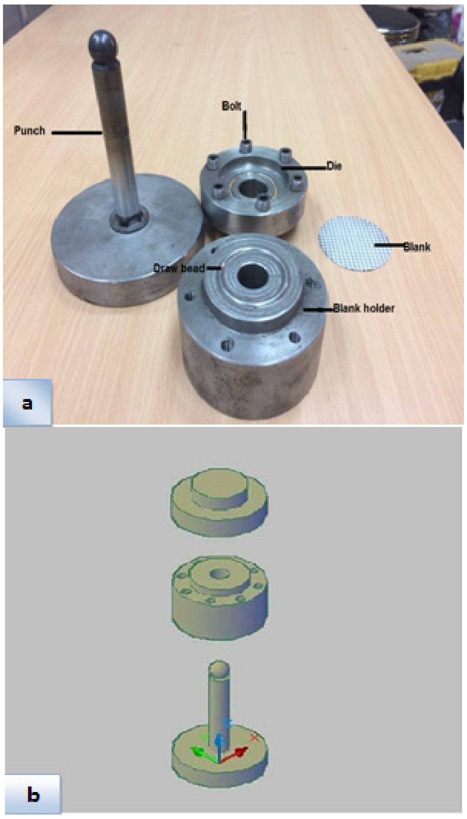



**Fig. 4. Stretching forming equipments used. a) physical tools representation, b) assembly view representation.**

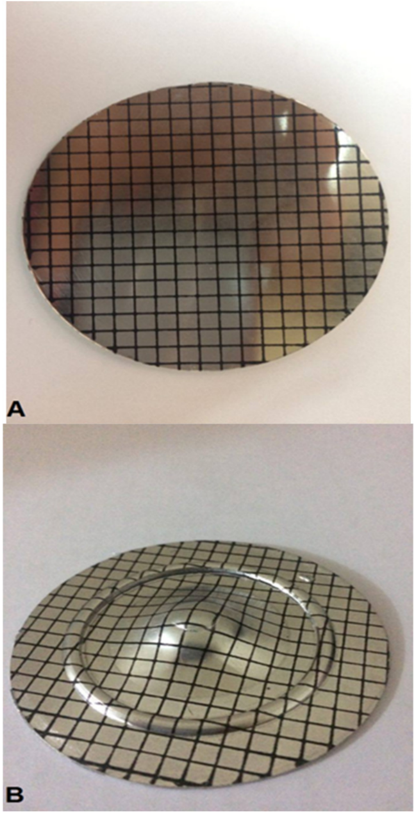



**Fig. 5. Specimen with grid, A. before bulge test, B. after bulge test.**

The undeformed sheet put between the die and blank holder, a hemispherical punch acts on the lower side of the sheet forcing it till cracks begin to appear in the bulge cup. The distance at punch in its movement is referred to as the Erichsen drawing index IE (index Erichsen) and it is a measure of the formability of the sheet during stretch forming. After stretching the dimensions of grid marked on the bulge cup with change and in order to determine the values of principal strains must measure the dimensions of grid near in the crack region and in same way used in the tensile test can measure the major and minor strain in the bulge test as shown in the table 3. The specimen after and before the bulge test is shown in figure 5.

**Table 3,**
**Values of principal strains in the bulge test.**

| Index Erichen | $\epsilon_1$ | $\epsilon_2$ | $\epsilon_3$ |
|---|---|---|---|
| 8.38mm | 0.172 | 0.159 | -0.325 |

Both tests have been done in the University of Technology - Production Engineering and Metallurgy, the speed used in the both tests are same and equal to the 0.5mm/ min. As mentioned above the forming limit diagram is plotted by combining the results of strain measurements in the tensile test (uniaxial tensile) on the left side of the diagram with positive major and negative minor strains, bulge test (biaxial tension) on the right side of the diagram with positive major and minor strains through the necking zone and plane strain condition where the strain hardening exponent represents the major strain in this condition. The forming limit diagram (FLD) is shown in figure 6.

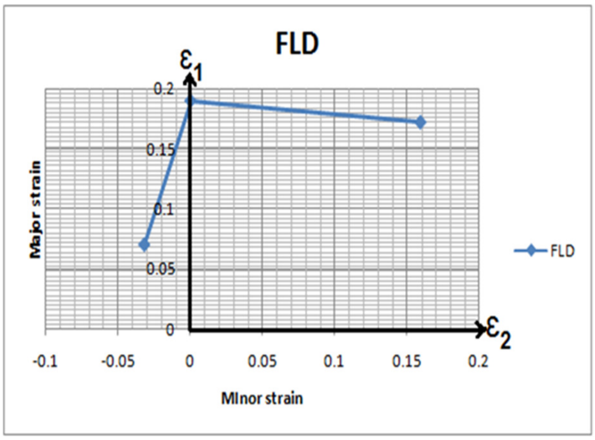
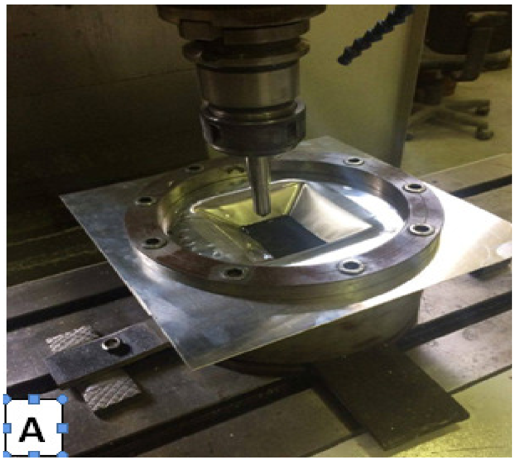



**Fig. 6. Forming limit diagram for AL1050 aluminum alloy.**

## 2.4 Incremental Sheet Metal Forming Test

Incremental sheet metal forming has demonstrated its great potential to form complex three dimensional parts without using a component specific tooling. The main aim of this study is to investigate single point incremental forming on CNC milling machine. The tests are conducted to measure the strains during ISMF operation and determine the effect of some process parameters on the strain distributions on the product. The equipments are used in this study to produce pyramid product are shown in figure (7a-7b). different tool shape are used in this study as shown in figure (8).



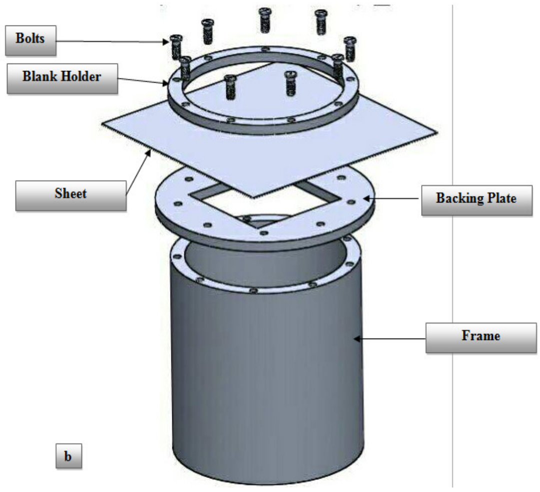




**Fig. 7. SPIF equipment used in the study, a) physical tools representation, b) assembly view representation.**

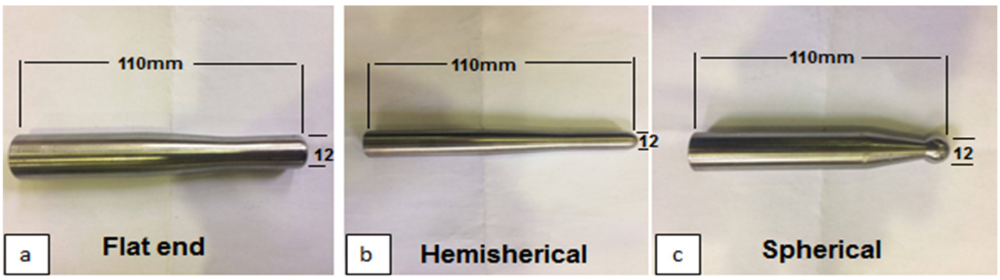



**Fig. 8. Forming tool used.**

### 2.4.1 Sheet Material

All experimental were performed with AL1050 Aluminum alloy, the initial size of the sheet used was (250mmX250mmX0.9mm) and the working area is 170mm according to the inner diameter of the frame, nine holes were machined and distributed uniformly along the perimeter of the sheet in order to ensure fixing the blank between the blank holder and frame by studs.

## 2.5 Measurement Procedures

### 2.5.1 Strain Measurement

There are a lot of methods to measure the deformation or strain. Grid marking method is one of the basically method for strain analysis in the sheet metal forming process. this method includes very small shape grid pattern (circle or square), whereas grid marking is the process of printing patterns on area. The forming process causes the grid pattern to deform and by measuring the dimensions of grid before and after deformation the principle strain determines [8].

In this research, the screen printing method was used to print the grid. Screen printing is one of the early methods for printing and is one of the easiest and cost effective methods for grid marking, the grid was printed on the lower surface area of sheet because it cannot resist the effect of forming process conditions such as rotational speed of spindle and friction. the sheets were printed with square patterns with dimensions (4mmX4mm) as shown in the figure (9). The image processing technique are used to measure the dimensions in the grid and this technique is an optical and non contacting for full-field strain measurement and can measure displacements and strains in the tensile test, bulge test and incremental sheet forming. MATLAB package was used by applying Matlab Image processing toolbox to investigate displacement and the strain by using of distinct grid on the sample surface.

**Fig. 9. Sheet metal with square grid.**

## 2.6 Design of Experimental (DOE)

In the incremental sheet forming process, it is important to investigation the effect of process parameters to determine the best conditions of process parameters. The influence of four parameters (feed rate, step size, tool shape and forming angle) on formability of the pyramid shape product and strain distributions over the product were analyzed by using the commercial software package MINTAB 16 (statistical software). Three process parameters (feed rate, step size and tool shape) each at three level while the last one is the angle forming with two level. The process parameters are evaluated by Taguchi's method. Factor control and their levels as shown in table (4). Nine experiments performed to produce the pyramid shape product according to the design of experimental Taguchi method. The layout of the design of the experiment matrix is shown in table (5).

**Table 4,**
**Propose control factors and their levels.**

| Factor | parameter | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| A | Tool shape | Flat end | hemispherical | Ball end |
| B | Step size | 0.3 | 0.5 | 0.7 |
| C | Feed rate | 800 | 1000 | 1200 |
| D | Forming angle | 55° | 45° | |

**Table 5,**
**Matrix layout of the experiments.**

| No. experiment | Step size | Feed rate | Tool shape | Forming angle |
|---|---|---|---|---|
| Ex1 | 0.3 | 800 | Flat end | 55°, 45° |
| Ex2 | 0.5 | 1000 | Flat end | 55°, 45° |
| Ex3 | 0.7 | 1200 | Flat end | 55°, 45° |
| Ex4 | 0.3 | 1000 | hemispherical | 55°, 45° |
| Ex5 | 0.5 | 1200 | hemispherical | 55°, 45° |
| Ex6 | 0.7 | 800 | hemispherical | 55°, 45° |
| Ex7 | 0.3 | 1200 | spherical | 55°, 45° |
| Ex8 | 0.5 | 800 | spherical | 55°, 45° |
| Ex9 | 0.7 | 1000 | spherical | 55°, 45° |

## 3. Results and Discussion

Newly novel sheet metal forming technique, incremental forming, have been introduced. It is based on utilizing of simple tool, which is moved over CNC controlled tool path. The product is manufactured by deforming the sheet locally. The incremental sheet metal forming process is still under development. The aim of this study is focused on the deformation occurs during forming of the sheet to produce the product and study the effect of the some process parameters on the formability in term of effective strains using Taguchi approach by using analysis of variance (ANOVA) and mean effect plot (MEP). In this test, all experiments performed to produce pyramid shape product, a frustum pyramid with top square base 100mmX100mm, bottom rectangle base 54.1mmX33.9mm and 33mm of height has been successfully produced by ISF, the pyramid is not symmetry in shape with four sides and two wall angles (45°, 55°) each match sides are equal in angles, this type of shape will reduce the number of experiments required to study the effect of forming angles due to two angles in the same product. The dimensions of the pyramid shape produced in this study are shown in figure (10).

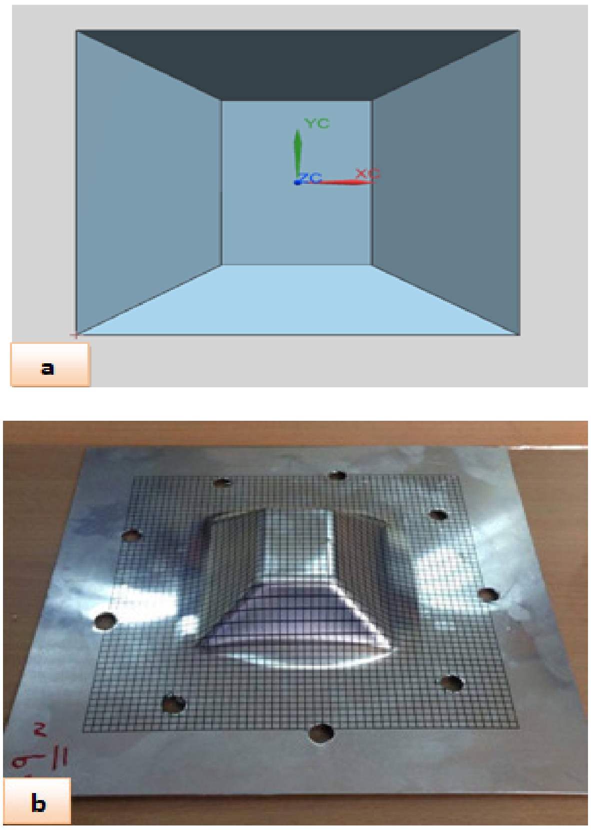



**Fig. 10. Product geometry, a) top view, b) formed shape**.

For the analysis of values of effective stains and strain distribution in the sheet deformed by ISF process, the following five regions were identified on the deformed sheets shown in figure (11).

Region 1: base of the sheet formed.
Region 2: top radius zone of the deformed sheet.
Region 3: wall zone of the deformed sheet.
Region 4: bottom radius zone of the deformed sheet.
Region 5: flange of the deformed sheet.

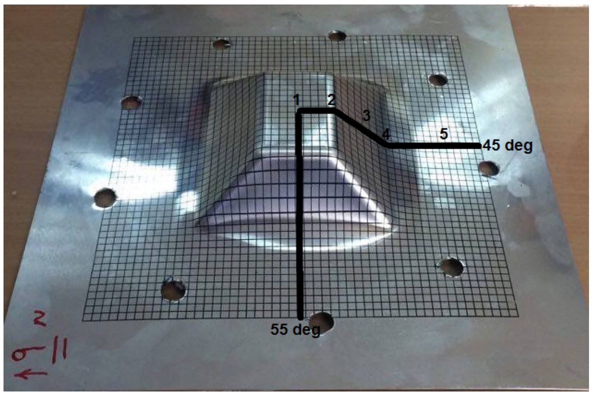



**Fig. 11. Deformed sheet with identified regions.**

The strains distribution over the length of deformation from region1 to region5 has been computed experimentally for two forming angles (55°, 45°) for all experiments. The author chooses arbitrary the experiment (3) in order to explain this distribution of strain, the condition used in this experimental as follows: spindle speed (1000 rpm), feed rate (1200mm/min), incremental step size (0.7mm) and with flat end head were used. Figure (11a-11b) represents the distribution of effective strain over the paths marked on the surface of the part for experiment (3). It is seen from this figure, that the value of effective strain is zero at base (region1), where very small deformation occurs in this area, which cannot be observed, and then there is some rise at the top radius zone (region 2), due to sever deformation (bending) in this region. Afterward, at wall zone, effective strain continues to increase to reach a maximum value at this region (region3) due to high tension stresses in the product wall, then the effective strain decrease in value in the bottom radius zone (region 4), finally reach to zero in the flange of product because there aren't any deformation this region (region 5). It is noted from the figure (12a-12b), two curves have the same trend but the values different due to differ in forming angles. Increase in the forming angle increase in the values of effective strain due to excessive deformation occurs in the high forming angle. The figure (13) shown the strain distributions over the length of formed sheet for all experiments in two forming angles used in this study. It is noted from the figure the all curves behaves the same trend with there are some different in the values of the effective strain.

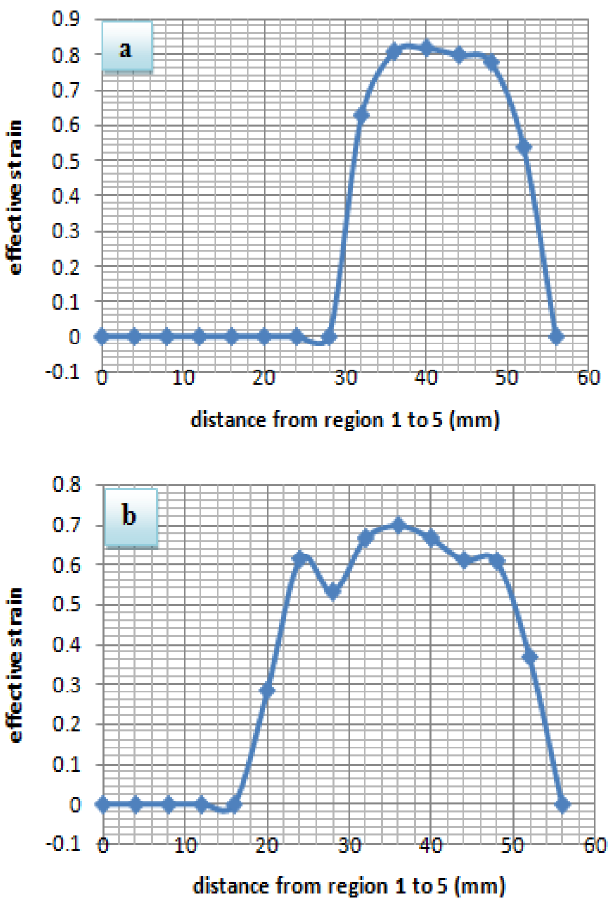
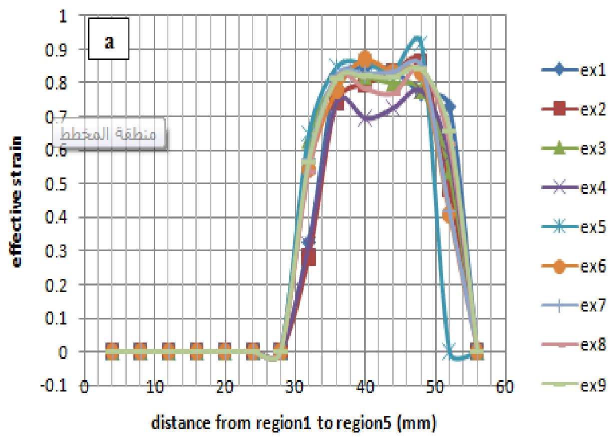



**Fig. 12. Strain distribution over the formed sheet for experiment (3), a) 55°, b) 45°.**



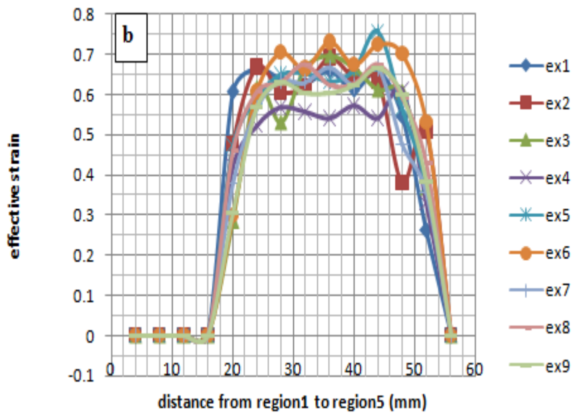




**Fig. 13. Strain distribution over the formed sheet for nine experiments, a) 55°, b) 45°.**

### 3.1 Quantitative Analysis for Formability.

The quantitative analysis of effective strains on 55° and 45° forming angles are consider in relation to the Main Effect Plot (MEP) and Analysis of Variance (ANOVA).

#### 3.1.1 Main effect plot for formability on 55° wall angle

MEP is a plot of the response variable means for each level of the factor. It is useful in visualizing which factors affect the response most to determine the significance of these factors. Figure (14) is shown the main effect plot of the three controlling factors (feed rate, step size, forming tool shape) on formability (in term of effective strain) on the 55° forming angle of the pyramid shape part. It is clear from the figure, the MEP indicates that the response effective strain increases as the factor (step size) converts from their low level 0.3mm to their high level 0.7mm, while in the other factor (tool shape) it is noticed increased when the shape factor converted from 0.3 to the 0.7 and then decreased to the 1. Whereas the response effective strain decreases when the feed rate factor moves from low level 800 rpm to the medium level 1000 rpm and increases when move to the high level 1200rpm.

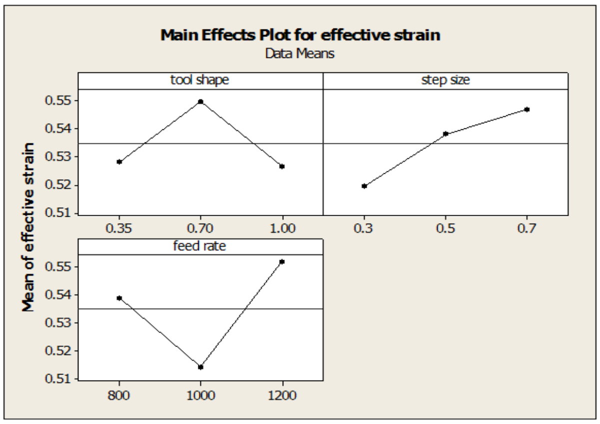



**Fig. 14. Main effect plot (Data means) for average effective strains on the 55° forming angle.**

The result of rank represent the arrangement of parameters affecting response effective strain are noted table (6). The ranks indicates the relative importance of each factor to the mean effective strains. The feed rate (rank1) is the factor that has large effect and is followed by step size (rank2), tool shape factor (rank3) respectively.

**Table 6,**
**Means larger results (55° forming angle).**

| level | Tool shape | Step size | Feed rate |
|---|---|---|---|
| 1 | 0.5282 | 0.5198 | 0.5388 |
| 2 | 0.5497 | 0.5379 | 0.5141 |
| 3 | 0.5267 | 0.5469 | 0.5518 |
| Delta | 0.0230 | 0.0271 | 0.0377 |
| Rank | 3 | 2 | 1 |

### 3.1.2 Analysis of variance for formability on 55° wall angle.

ANOVA is a way of portioning variability into identifiable sources of variation to study which source of variation significantly affects the response. In this study, three control factors are used factors (feed rate, step size, forming tool shape), therefore there would be three sources of variation control the required effective strains. ANOVA has a sharp criterion to select the significant parameter from three sources by analyzing the significant effect through F-fisher tester or probability value P-value. The analysis is carried out for the level of confidence of (β1=95%), therefore the level of significance is (β2=5%). Thus the source of variation is considered to be significant if its p-value smaller or equal to 0.05. the ANOVA table is created by Minitab program V16 was used to created the figure (15) which represents the percent of contributions of effects of factors. It is noted from the figure the feed rate is a significant factor and has large effect on effective strains with percentage contribution of 42.86% and followed by step size with 25.1% percentage contributions and finally the shape factor with 21.79%.

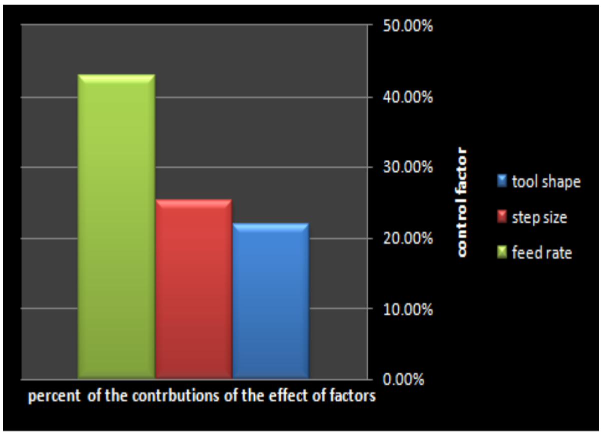



**Fig. 15. Percentage contributions of means (55° wall angle).**

### 3.1.3 Main effect plot for formability on 45° wall angle.

Figure (16) show the main effects of the three control factors on average effective strains on the 45° wall angle. From the figure in is noted that the effective strain little affected by the forming tool shape. However, the highest value of effective strain can be obtained when used hemispherical end head of the forming tool while the lowest value can be obtained when used spherical end. Whereas the response effective strain increases when the step size factor moves from low level 0.3 mm to the medium level 0.5 mm and decreases when move to the high level 0.7mm. the feed rate also has effect on the effective strain , as its indicated, when increasing the feed rate, the effective strain decreases.

Table (7) is shown response for Means larger is better (45° forming angle). The feed rate (rank1) is the factor that has large effect and is followed by step size (rank2), tool shape factor (rank3) respectively.

**Table 7,**
**Means larger results (45° forming angle).**

| level | Tool shape | Step size | Feed rate |
|---|---|---|---|
| 1 | 0.4711 | 0.4522 | 0.4914 |
| 2 | 0.4754 | 0.4816 | 0.4506 |
| 3 | 0.4740 | 0.4747 | 0.4665 |
| Delta | 0.0106 | 0.0294 | 0.0408 |
| Rank | 3 | 2 | 1 |

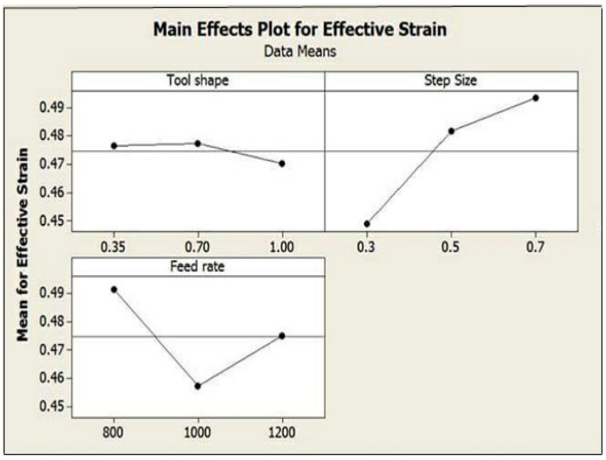



**Fig. 16. Main effect plot (Data means) for average effective strains on the 45° forming angle.**

### 3.1.4 Analysis of Variance for Formability on 45° Wall Angle

Figure (17) represents the percent of contributions of effects of factors. It is noted from the figure the feed rate is a significant factor and has large effect on effective strains with percentage contribution of 51.42% and followed by step size with 30.60% percentage contributions and finally the shape factor with 10.54%.

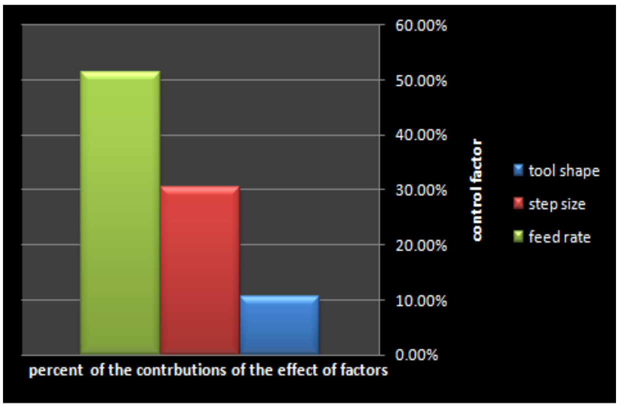



**Fig. 17. Percentage contributions of means (45° wall angle)**

## 4. Conclusions

The main conclusions which can be deducted from this study follows:

1. The forming limit diagram is suitable test for determine the formability of materials sheet (Al1050) processed by single point incremental forming process.
2. The formability ( in term of effective strain ) has been investigated in single point incremental forming process. The process parameters such as tool shape, step size and feed rate have most effect on the formability, it is noted that there are some fluctuation in values.
3. There are small effective strains in the base and flange region on the final product due to small deformation occurs in this regions. High values of tensile stress and effective strain computed on the wall product due to excessive deformation occurs in this region.
4. The feed rate is a parameter that has large effect on the values of the effective strain and is followed by step size and tool shape.
5. The maximum and minimum average effective strain computed on the 55° forming angle are (0.580, 0.399) respectively. While the maximum and minimum average effective strain computed on the 45° forming angle are ( 0.412, 0.324) respectively.

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# بحث تأثير متغيرات العملية على قابلية تشكيل الأجزاء المنتجة عن طريق تشكيل نقطي تزايدي

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**الخلاصة**

عملية التشكيل ألتزايدي لشرائح المعدنية هي عملية تصنيع متقدمة ذات مرونة تستخد□ لإنتاج أشكال ثلاثة الإبعاد المعقدة بدون ا□تخدا□ قوالب خاصة بشكل المنتج كما في عمليات التشكيل التقليدية. حيث توجد العديد من العوامل التي لها تأثير على هذه العملية درا□ة تأثير بعض من هذه العوامل على توزيع الانفعالات المتولدة على طول □طح المنتج هو هدف هذا البحث, لضمان تحقيق هذا الهدف فان هناك ثلاثة عوامل متمثلة بـ ( شكل عدة التشكيل ومعدل التغذية وحجم الخطوة التزايدية ) تم درا□ة تأثيرها على توزيع الانفعالات على□طح المنتج لثلاثة مستويات من القيم. أن قيا□ات الانفعالات أنجزت بو□اطة تكنولوجيا معالجة الصور با□تخدا□ برنامج الماتلاب. إن أهمية هذه العوامل من حيث تأثيرها على النتائج المستخرجة حللت بوا□طة نوعين من طرائق التحليل الإحصائية هي طريقة تحليل التباين (ANOVA) وطريقة ر□م معدل التأثير (MEP). كل التجارب نفذت على شرائح من □بيكة الألمونيو□ (AL1050) وبسمك 0.9 ملم وعن طريق ا□تخدا□ مكائن التحكم الرقمي ذي ثلاثة محاور لإنتاج منتج هرمي مربع القاعدة. أشارت النتائج على إن معدل التغذية هو الأكثر تأثير على قابلية التشكيل وبنسبة مساهمة تصل إلى (42.86%, 51.42%) يليه حجم الخطوة التزايدية لعدة بنسبة مساهمة 25.1%, (30.60%) وأخيرا شكل عدة التشكيل المستخدمة بنسبة مساهمة (10.54%, 21.79%) على السطوح المنتجة في زوايا تشكيل (45°, 55°) على التوالي . أعلى واقل قيمة لمعدل الانفعال الفعال تم الحصول عليها عند ا□تخدا□ زاوية تشكيل (55°) هي (0.399, 0.580) على التوالي بينما أعلى واقل قيمة لمعدل الانفعال الفعال تم الحصول عليها عند زاوية تشكيل (45°) هي (0.324, 0.412) على التوالي.