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An Investigation Study of Tool Geometry in Single Point Incremental Forming (SPIF) and their effect on Residual Stresses Using ANOVA Model

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Abstract

Incremental forming is a flexible sheet metal forming process which is performed by utilizing simple tools to locally deform a sheet of metal along a predefined tool path without using of dies. This work presents the single point incremental forming process for producing pyramid geometry and studies the effect of tool geometry, tool diameter, and spindle speed on the residual stresses. The residual stresses were measured by ORIONRKS 6000 test measuring instrument. This instrument was used with four angles of (0º,15º,30º, and 45º) and the average value of residual stresses was determined, the value of the residual stress in the original blanks was (10.626 MPa). The X-ray diffraction technology was used to measure the residual stresses. The sheet material used was Aluminum alloy (AL1050) with thickness of (0.9 mm). The experimental tests in this work were done on the computer numerical control (CNC) vertical milling machine. The extracted results from the single point incremental forming process were analyzed using analysis of variance (ANOVA) to predict the effect of forming parameters on the residual stresses. The optimum value of the residual stresses (55.024 MPa) was found when using the flat end with round corner tool and radius of (3 mm), wall angle of (55°) and a rotational speed of the tool of (800 rpm). The minimum value of the residual stresses (24.389MPa) was found when using hemispherical tool with diameter of (12 mm), wall angle of (45°) and a rotational speed of the tool of (800 rpm).

Keywords: *ANOVA, CNC milling machine, Residual Stresses, SPIF process, Taguchi method.*

1. Introduction

Single Point Incremental Forming (SPIF) process has been developed from sheet metal spinning, sheet metal shear moving and hammering with included CNC system to control the forming tool motion [1]. SPIF is a comparatively recent bed sheet forming process which enables forming of complicated shapes without specific dies utilizing only a single point tool and a standard three-axis CNC machine [2].

SPIF is a progressive and adaptable bed sheet metal-forming technology that uses layered manufacturing basis. That changes the part geometry data for a several parameters of 2D layers, and after that the plastic-local deformation is done layer-by-layer over the CNC machine motions of the simple forming tool to manufacture products with complicated shapes as demonstrated in figure (1) [3, 4].

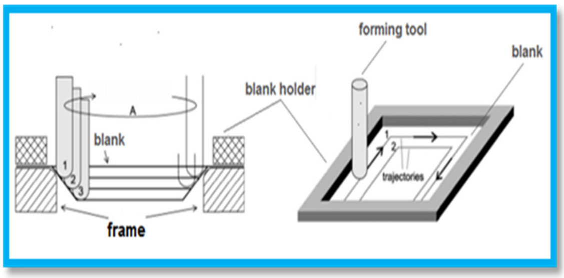


Fig. 1. Representation of SPIF process [5].

2. Literature Review

Many researchers studied the effect of SPIF process parameters on the residual stresses, but in this work will studying the effect of tool geometry on the residual stresses, some of related works are presented below:

Isaac Jimenez and et al [6] presented the effect of the residual stresses along the aluminum products which produced by the SPIF process. The residual stresses on both outer and inner surfaces were measured by X-Ray diffraction technique. The residual stresses measured were changed from tensile to compressive stresses. The data of experimental is indicated the residual stresses effects on the micro structural of the aluminum products. Arshpreet Singh and Anupam Agrawal [7] presented the comparison between traditional and ISM bending/stretch forming in the residual stresses, deforming forces and geometrical contradiction. Also, the influence of prior anisotropy in bending comparisons of the spring back and deforming forces contained. Deforming forces was obtained in incremental sheet metal bending is less than obtained in traditional bending. Residual stress generated over the product in incremental sheet metal bending was less in comparison of traditional bending process. The results showed that it is possible to rely on the incremental sheet metal forming process and commercialized as an alternative method to traditional deformation processes. D. M. Neto and et al [8] presented the ISMF process of aluminum alloy (AA7075) to produced simple truncated cone. The finite element model was utilized to analyze the stress and strain. The forming force, the thickness and an apportionment of plastic strain extracted from numerical model was validated with the results extracted from experimental. To be able to assess the through-thickness gradients effectively, the blank was modeled with solid FEM. A negative mean stress under the tool was induced in the small contact area between the sheet and forming tool, which delay the occurrence of ductile fracture. A. S. Bedan and et al [9] studied the effect of forming parameters (rotational speed, feed rate, and vertical depth) on residual stresses which induced in parts made of Aluminum (Al 1050) alloy. ANOVA model used to know the contribution of rotational speed, feed rate, and vertical depth with respect to residual stresses was (63.7, 4.3, and 32) % respectively. Aseel Hamad Abed and et al [10] presented the multilayer SPIF process and using top plate with three thicknesses (0.5, 0.7, and 0.9) mm, different types of lubrication used between two plates to predict the influence of these variables on residual stresses in bottom plate. The results explained an inversely relationship between the thickness of top plate and residual stresses. The minimum residual stresses were induced when using the graphite with grease lubricant between two plates.

3. Residual Stresses

It is the stresses that stay in a body which is steady and in equilibrium with surroundings. The residual stresses rely on the interaction with external loads, they can effect on the interaction between the mechanical behavior and external loads. Also they can effect on the lifetime and mechanical behavior of products by negative or positive method [11].

3.1 X-ray Diffraction

This method used to calculate the residual stress depending on the measuring of angles at the maximum intensity of diffracted which happen whenever a crystalline specimen is submitting to x-rays. From these angles, Bragg's law is utilized to get inter planar spacing of the planes diffraction. When the residual stresses exist in the specimen, inter planar spacing will be various than that of unstressed state. The difference between two states is proportionate to the residual stress amount [12].

Whenever a beam of x-rays monochromatic fails over the polycrystalline materials, the diffraction happens of those crystallites that are oriented to meet the Bragg's law [13]:

$$\lambda = 2d\sin\theta \qquad \dots(1)$$

Where:

λ: The incident radiation wavelength.

d: Inter planar spacing.

θ: The angle of the event beam makes with the diffracting plane (Bragg angle).

The acting single stress measure in some direction in the surface σ_θ. Shows the strain along oblique line of isotropic solid according to elasticity theory (as shown in figure (2)) is [14]:

$$\varepsilon_{\emptyset\Psi} = \frac{1+v}{E}(\sigma_1\cos^2\emptyset + \sigma_2\sin^2\emptyset)\sin^2\Psi - \frac{v}{E}(\sigma_1 + \sigma_2) \qquad \dots(2)$$

Use the strains to evaluate the stresses when evaluation the strains in conditions of spacing of inter planar and then it can be shown that

$$\sigma_\emptyset = \frac{E}{(1+v)\sin^2\Psi}\left(\frac{d_\Psi - d_n}{d_n}\right) \qquad \dots(3)$$

Where:

$\varepsilon_{\emptyset\Psi}$: Strain measured in the $\emptyset\Psi$ direction.

v: Poisson’s ratio.

E: Elastic modulus.

σ_1, σ_2: Principal stresses acting in the principal directions.

∅: The angle between the projection in the plane of normal diffracting plane and a fixed direction in that plane of the specimen.

Ψ: The angle between the normal diffracting plane and the normal of the specimen.

d_Ψ: The spacing of inter planar of planes with angle Ψ to the surface.

d_n: The spacing of inter planar of planes to the surface.

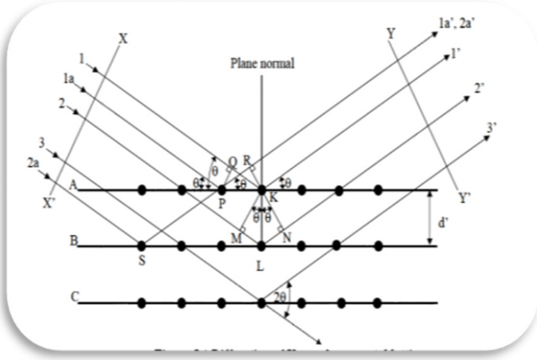


Fig. 2. Residual stress measurement [14].

4. Experimental Work

4.1 Geometry Construction of Products

The geometry of the products is pyramid shape with total depth of (35 mm) and with three different wall angle (45º, 50º, and 55º) as shown in figure (3). The CAD model of the products illustrated in figure (3) was created by the following steps:

- Drawing the desired geometry of product by AutoCAD program and save the drawing in the extension format (dwg) for example (file name.dwg).
- Opening the saved drawing in the Solid Work program and then save the drawing in the extension format (part) for example (file name.prt).
- Opening the file name with the extension format (part) in the CAD/CAM package (Siemens UGS-NX9).

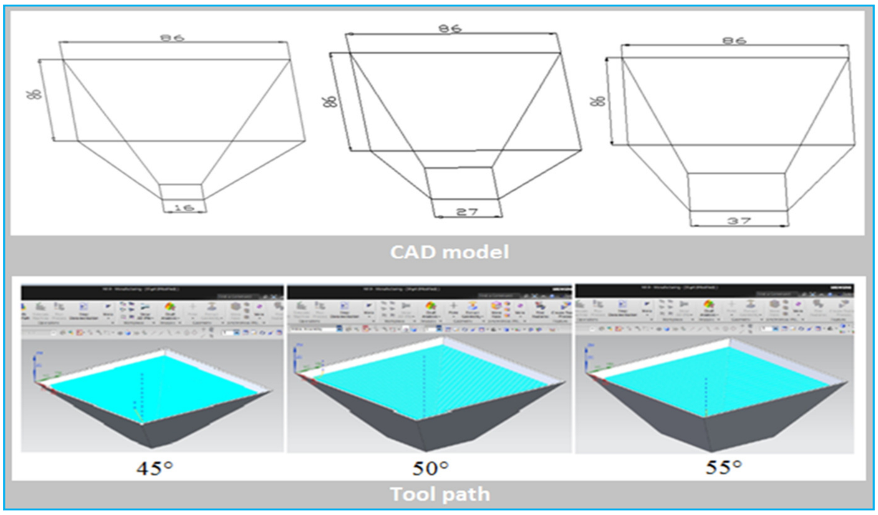


Fig. 3. The CAD geometry and tool path of products.

4.2 Sheet Material

The sheet material used in this work is Aluminum alloy (AL1050) with thickness of (0.9 mm). The initial dimensions of the blank were (225×225 mm). The chemical composition and mechanical properties are illustrated in the tables (1) and (2).

Table 1,
Chemical composition of the sheet material

Material		Al%	Si%	Fe%	Cu%	Mn%	Mg%	Cr%	Ni%	Zn%
AL 1050	Measured	99.5	0.142	0.315	0.013	0.013	0.001	0.001	0.003	0.006
	ASTM Standard	≤99.5	≤0.25	≤0.4	≤0.05	≤0.05	≤0.05	≤0.03	≤0.03	≤0.05

Table 2,
Mechanical properties of the sheet material

Material		Yield Stress (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation %	Poisson's Ratio
AL 1050	Measured	71	86	72	4.1	0.33
	ASTM Standard	65-78	80-100	70-75	3.5-4.2	0.33

4.3 Forming Frame and Forming Tools

Forming frame was utilized to fixate the blank on the CNC milling machine table. Forming frame is consisting of several components as shown in the figure (4). The Forming tools that used in this work consist of three different geometries with different sizes to study the effect of these tools on the residual stresses. The first type was ball end with three diameters (8, 10, and 12) mm. The second type was hemispherical shape with three diameters (8, 10, and 12) mm. And the last type was flat end with round corner of different radius (3, 4, and 5) mm. Figure (5) illustrates these tools.

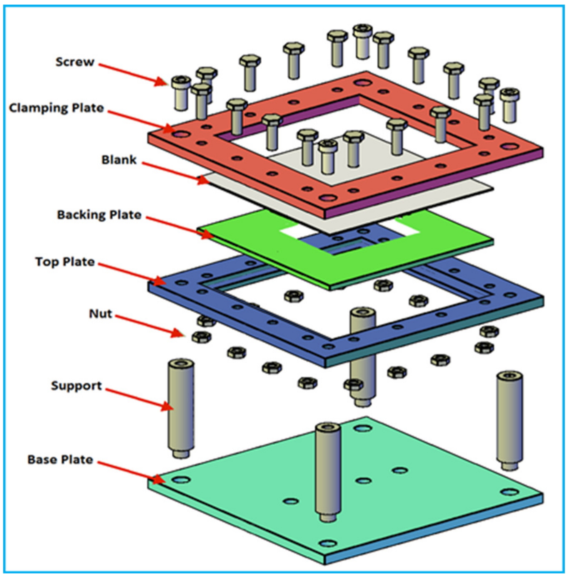


Fig. 4. Assembly view of the forming frame.

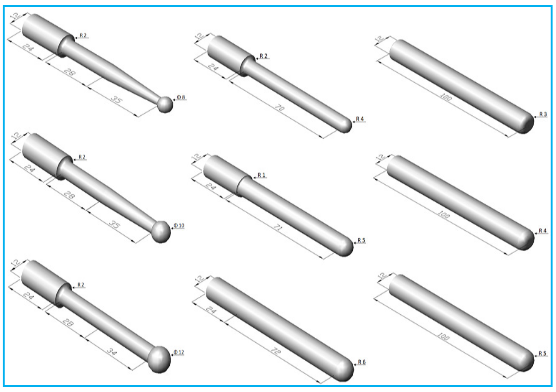


Fig. 5. The tools used.

4.4 Forming Tests

The SPIF processes of this work were performed at the university of technology/ training center and workshops, using 3-axis "C-Tek" CNC milling machine as shown in figure (6). The feed rate of (800 mm/min) and vertical depth of (1/3 mm) were used with tests. In this work, the used lubrication type is PENNZOIL (SAE 5W-30). Figure (7) is shown the products, which were produced by the ball end, hemispherical, and the flat with round corner tools.

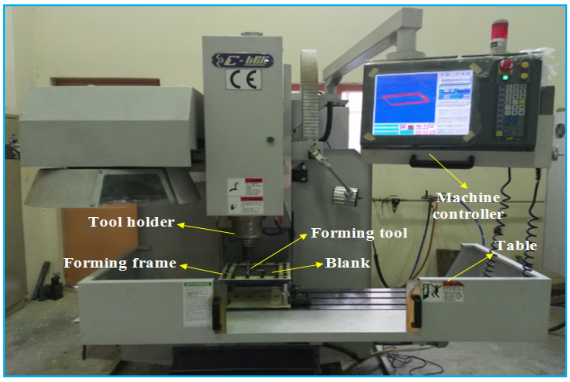


Fig. 6. CNC milling machine utilized in experimental work.

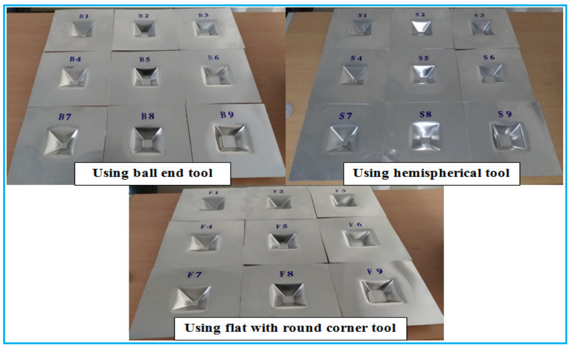


Fig. 7. The products produced using three different geometries of tool.

5. Residual Stress Test

The test samples were prepared from the pyramid wall in circle shape with diameter of (30 mm) using die of wood identical to half of the shape of the product and this process performed on drilling machine as shown in the figure (8). The residual stress test was performed in the "Ministry of Construction and Housing- National Center for Structural Laboratories" by utilized ORIONRKS 6000 test measuring instrument as shown in figure (9). The X-ray diffraction technology was used to measure the residual stress.

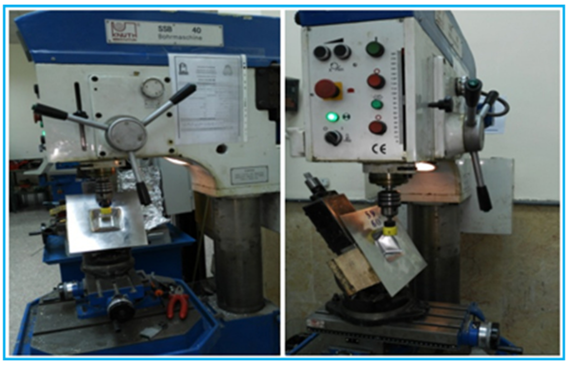


Fig. 8. Preparing the test samples.

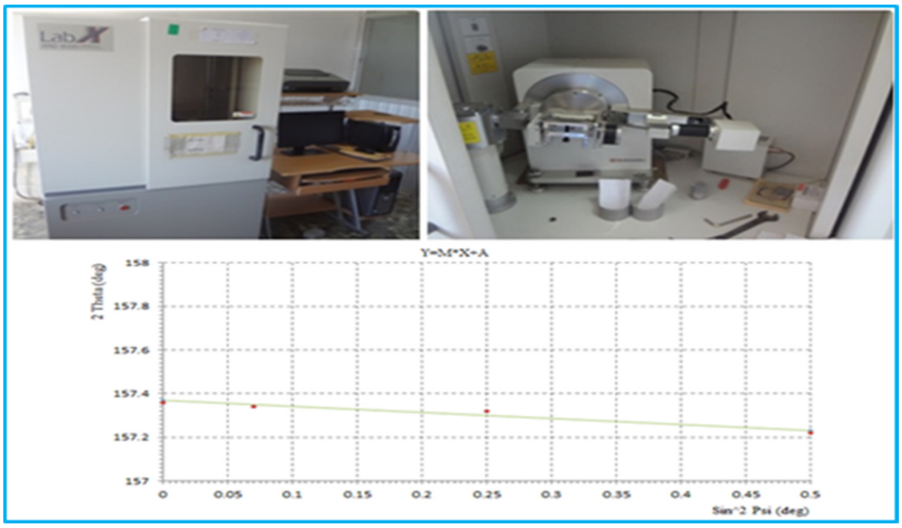


Fig. 9. Residual stress measurement result.

6. Design of Experimental

In this work, the Taguchi's (L9) orthogonal array was used for three types of tools. The processes parameters and levels for the ball end, hemispherical and the flat with round corner tools are illustrated in the tables (3-7). Figure (10) presents the relationship between the results extracted from experimental work.

Table 3,
Forming parameters and their levels for ball end and hemispherical tools

Parameters	Units	Level 1	Level 2	Level 3
Diameter	**mm**	8	10	12
Angle	**o**	45	50	55
Spindle Speed	**rpm**	0	400	800

Table 4,
Forming parameters and their levels for the flat with round corner tools

Parameters	Units	Level 1	Level 2	Level 3
Radius	**mm**	3	4	5
Angle	**o**	45	50	55
Spindle Speed	**rpm**	0	400	800

Table 5,
Experimental layout using L9 orthogonal array and corresponding results for ball end tool.

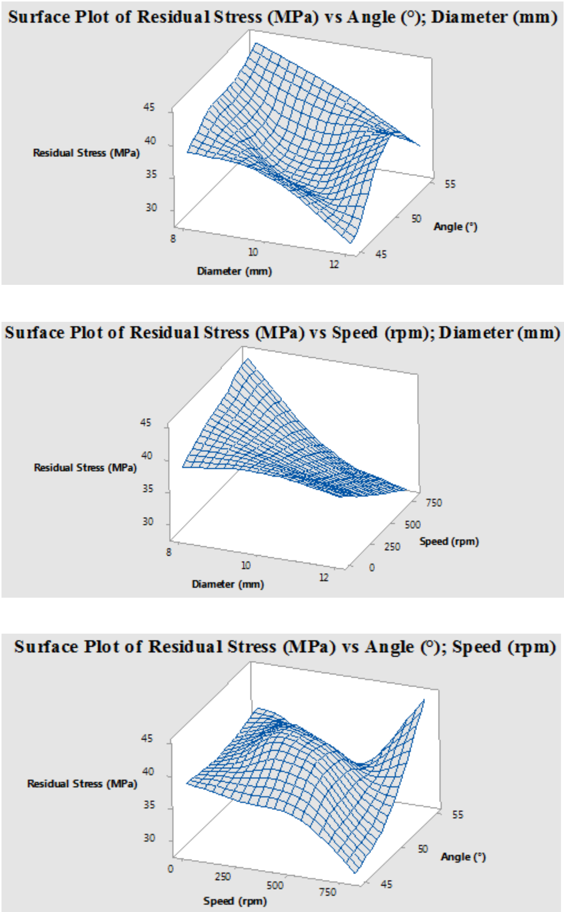
Experimental No.	Process Parameters			Response Value	Machining Time (min)
	Diameter (mm)	Angle (º)	Spindle Speed (rpm)	Residual Stress(MPa)	
1	1	1	1	38.556	32.09
2	1	2	2	42.023	34.16
3	1	3	3	44.857	36.26
4	2	1	2	36.797	31.01
5	2	2	3	32.922	32.58
6	2	3	1	39.66	34.59
7	3	1	3	28.605	29.54
8	3	2	1	37.98	31.41
9	3	3	2	32.962	33.32

Table 6,
Experimental layout using L9 orthogonal array and corresponding results for hemispherical tool

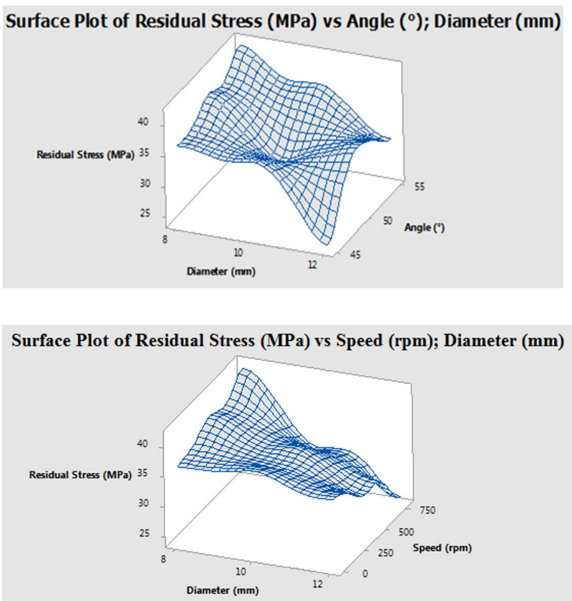
Experimental No.	Process Parameters			Response Value	Machining Time (min)
	Diameter (mm)	Angle (º)	Spindle Speed (rpm)	Residual Stress(MPa)	
1	1	1	1	36.427	32.09
2	1	2	2	39.274	34.16
3	1	3	3	41.722	36.26
4	2	1	2	35.79	31.01
5	2	2	3	30.452	32.58
6	2	3	1	37.666	34.59
7	3	1	3	24.389	29.54
8	3	2	1	34.966	31.41
9	3	3	2	30.508	33.32

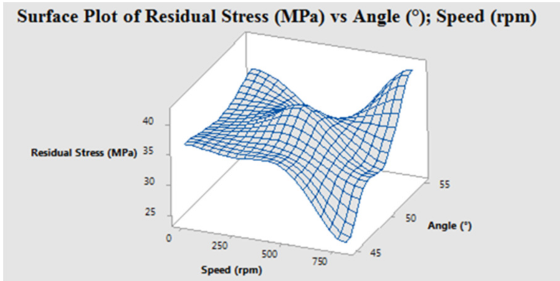
Table 7,
Experimental layout using L9 orthogonal array and corresponding results for the flat tool.

Experimental No.	Process Parameters			Response Value	Machining Time (min)
	Radius (mm)	Angle (º)	Spindle Speed (rpm)	Residual Stress(MPa)	
1	1	1	1	49.104	28.11
2	1	2	2	53.972	30.25
3	1	3	3	55.024	32.46
4	2	1	2	47.078	28.36
5	2	2	3	43.148	30.44
6	2	3	1	51.796	32.58
7	3	1	3	39.813	29.02
8	3	2	1	48.261	31.04
9	3	3	2	43.802	33.09

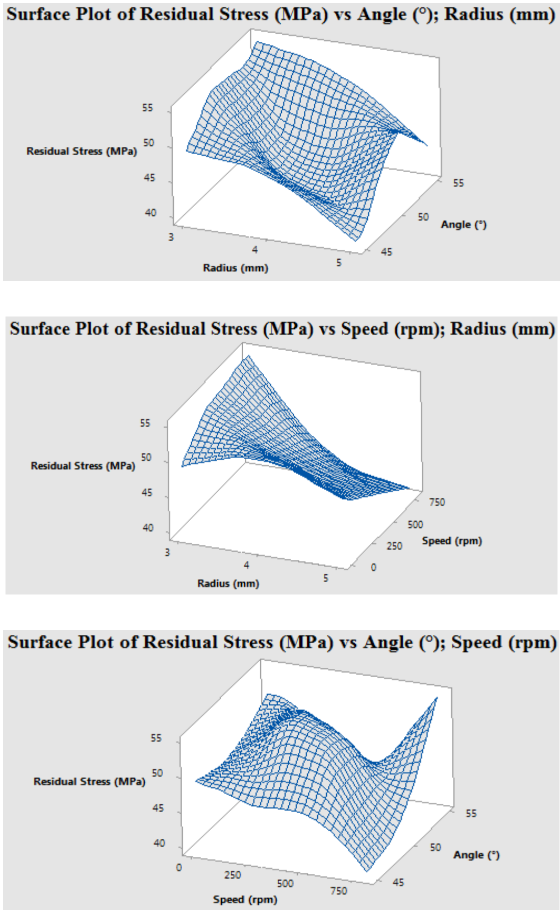


(a)





(b)



(c)

Fig. 10. The results using: (a) Ball end tool. (b) Hemispherical tool. (c) Flat with round corner tool.

7. Optimization of Forming Parameters

In this work, the Taguchi approach is apply using Mini Tab package. The best parameters of forming are found according to Signal to Noise (S/N) ratio. Depended on the kind of characteristics performance, Taguchi categorizes the characteristics performance to three various types: the larger the better (LB), the nominal the better (NB), and the smaller the better (SB). For find the optimum forming parameters to give the best residual stresses, the smaller the better (SB) was used. Equation (4) is used to determine the S/N ratio. The effect of each process parameters at different levels and the mean S/N ratio was illustrated in table (8). And the ANOVA results for the experimental work is calculated and listed in table (9).

$$\frac{S}{N} = -10\ \log\left[\frac{1}{n}\sum_{i=1}^{n} {Y_i}^2\right] \qquad \ldots(4)$$

Where:

i: No. of trial.

Y_i : Measured value of quality characteristic for i[th] trial condition.

n: No. of repetitions.

S: Sum of degree of freedom for process parameters.

$$DOF\ within\ group = E - 1 - S \qquad \ldots(5)$$

Where:

E: No. of experimental test.

S: Sum of DOF for process parameters.

The relationship between the process parameters and mean response (Residual stresses) can be demonstrated in figure (11) and the interaction between the SPIF processes parameters and the residual stresses are showed in the figure (12).

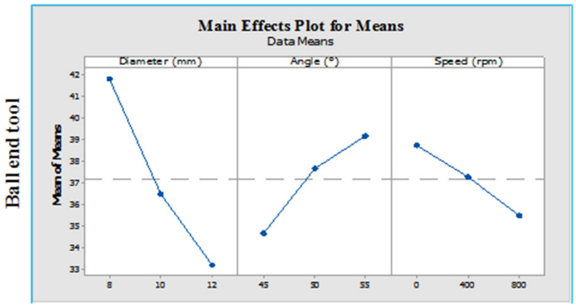
Table 8,
Results for individual characteristic of mean response and S/N ratio

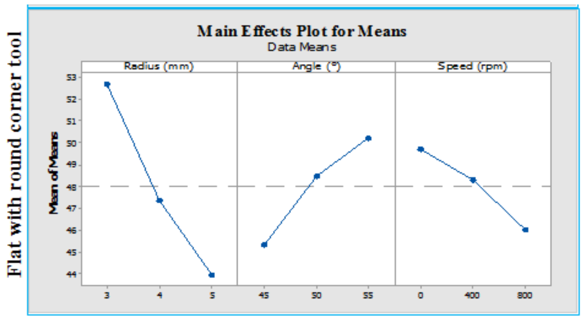
Ball end tool		**Mean response**			**S/N ratio**		
		Diameter	**Angle**	**Speed**	**Diameter**	**Angle**	**Speed**
	Level 1	41.81	34.65	38.73	-32.41	-30.72	-31.76
	Level 2	36.46	37.64	37.26	-31.21	-31.47	-31.38
	Level 3	33.18	39.16	35.46	-30.36	-31.79	-30.84
	Delta	8.63	4.51	3.27	2.05	1.07	0.92
	Rank	1	2	3	1	2	3
Hemispherical tool		**Mean response**			**S/N ratio**		
		Diameter	**Angle**	**Speed**	**Diameter**	**Angle**	**Speed**
	Level 1	39.14	32.20	36.35	-31.84	-30.02	-31.21
	Level 2	34.64	34.90	35.19	-30.76	-30.81	-30.88
	Level 3	29.95	36.63	32.19	-29.44	-31.20	-29.94
	Delta	9.19	4.43	4.17	2.40	1.19	1.27
	Rank	1	2	3	1	3	2
Flat with round corner tool		**Mean response**			**S/N ratio**		
		Radius	**Angle**	**Speed**	**Radius**	**Angle**	**Speed**
	Level 1	52.70	45.33	49.72	-34.43	-33.09	-33.93
	Level 2	47.34	48.46	48.28	-33.48	-33.67	-33.64
	Level 3	43.96	50.21	46.00	-32.83	-33.98	-33.17
	Delta	8.74	4.88	3.73	1.59	0.88	0.76
	Rank	1	2	3	1	2	3

Table 9,
ANOVA results of the residual stresses

	Source of variance	**Degree of freedom**	**Sum of squares (ss)**	**Variance (V)**	**Contribution on (P%)**
Ball end tool	**Diameter**	2	113.86	56.93	56.74
	Angle	2	31.55	15.78	15.72
	Speed	2	16.10	8.050	8.02
	Within group	2	39.16	19.58	19.52
	Total	8	200.67		100
Hemispherical tool	**Source of variance**	**Degree of freedom**	**Sum of squares (ss)**	**Variance (V)**	**Contribution on (P%)**
	Diameter	2	126.6	63.30	56.25
	Angle	2	29.90	14.95	13.28

	Speed	2	27.72	13.86	12.32
	Within group	2	40.85	20.425	18.15
	Total	8	225.07		100
	Source of variance	**Degree of freedom**	**Sum of squares (ss)**	**Variance (V)**	**Contribution on (P%)**
Flat with round corner tool	**Radius**	2	116.57	58.29	55.58
	Angle	2	36.61	18.31	17.46
	Speed	2	21.18	10.59	10.10
	Within group	2	35.38	17.69	16.86
	Total	8	209.74		100





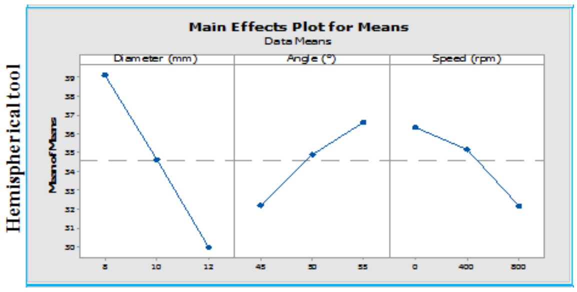
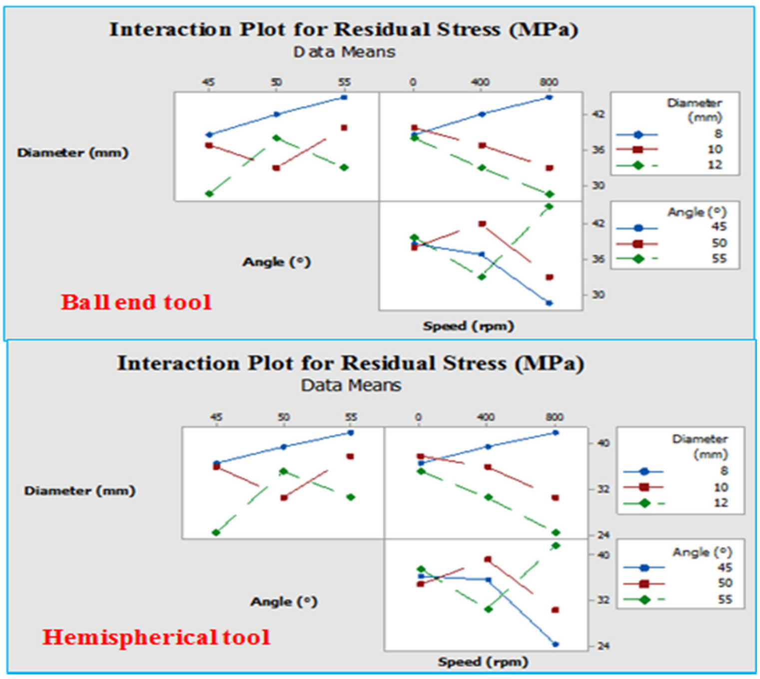


Fig. 11. Relationship between process parameters and mean residual stresses.



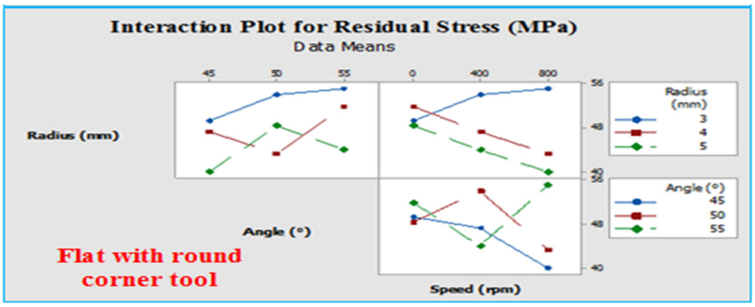


Fig. 12. The interaction between the processes parameters and the residual stresses.

8. Result and Discussion

The residual stresses are defined as the mechanical stresses and the best way to measure them is the experimental approach. There are two types of the residual stresses: tensile residual stresses and compressive residual stresses. A prefer type of the residual stresses is a compressive residual stresses because it leads to close the crack and increase the fatigue resistance for product. Mostly, in SPIF processes the type of the residual stresses is tensile residual stresses. Thus, the preferred value of the residual stresses is a low value.

Figure (11) showed that the residual stresses are inversely proportional to the tool diameter and rotational speed of the tool in all three cases for tools geometry used. While the relationship between the residual stresses and the wall angle of the pyramid is directly proportional.

The residual stresses in the wall of the pyramid produced are decrease with increase of the tool diameter because increase in the contact area between the tool and sheet that leads to distribute the stresses and non-concentration in specific area.

When the wall angle was increase, the thickness of the pyramid wall is decrease which leads to increase of the residual stresses in wall because concentration in small area.

The effect of the rotational speed of the tool on the residual stresses in the product is same the effect of the tool diameter on it. When the rotational speed of the tool is zero, the residual stresses were at its highest values. And when the rotational speed is increases, the residual stresses are decrease because the heat was generated at high speed which leads to distribute the stresses in the wall.

9. Conclusions

Al 1050 sheet were incremental formed under different forming tool geometry and their effects studies, the following conclusions were drawn from the study:

1-From the extracted results, the increase of the tool diameter and the rotational speed of the tool will reduce the residual stresses. While the increase in the wall angle will increase the residual stresses.

2-The optimum level of parameter for minimum the residual stresses was found with hemispherical tool at 3rd level of tool diameter parameter, 1stlevel of wall angle parameter and 3rd level of rotational speed parameter. Therefore, these levels of parameters are giving the best values of residual stresses in SPIF processes of aluminum sheet (AL1050).

3-The influence of process parameters on the residual stresses was indicated using analysis of variance (ANOVA). The results indicated the contribution of tool diameter, wall angle and rotational speed with respect to the residual stresses is (56.74%, 15.72% and 8.02%) respectively when used ball end tool, (56.25%, 13.28% and 12.32%) respectively when used hemispherical tool, and (55.58%, 17.46% and 10.10%) respectively when used the flat with round corner tool.

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دراسة هندسية شكل العدة في عملية التشكيل النقطي التزايدي وتأثيرها على الاجهادات المتبقية الناتجة باستخدام نموذج تحليل التباين (ANOVA)

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الخلاصة

□عد عملية التشكيل التزايدي عملية مرنة لتشكيل الصفائح المعدنية باستخدام ادوات بسيطة والتي فيها□تعرض الصفيحة المعدنية لتشويه منتظم على طول مسار عدة محدد مسبقاً وبدون استخدام القوالب. يستعرض هذا العمل عملية التشكيل النقطي التزايدي المستخدمة لإنتاج شكل هرمي ودراسة□أثير شكل العدة، قطرها وسرعة الدوران على الاجهادات المتبقية□م قياس الاجهادات المتبقية بوساطة جهاز (ORIONRKS 6000). يعمل هذا الجهاز مع أربع زوايا هي (صفر، ١٥، ٣٠، و٤٥ درجة) ويؤخذ معدل الاجهادات المتبقية، قيمة الاجهادات المتبقية في الصفيحة الاصلية (١٠,٦٢٦ ميكاياسكال). □ستخدم□قنية□شتت الاشعة لقياس الاجهادات المتبقية. الصفيحة المعدنية المستخدمة هي سبيكة الالمنيوم (AL1050) بسمك (٠,٩ ملم). وأجريت الاختبارات العملية في هذا العمل على ماكينة التفريز العمودية المبرمجة. النتائج المستخرجة من عملية التشكيل النقطي التزايدي□م□حليلها باستخدام انموذج□حليل التباين لمعرفة□أثير متغيرات عملية التشكيل على الاجهادات المتبقية□م ايجاد اعلى قيمة للإجهادات المتبقية (٥٥,٠٢٤ ميكاباسكال) عند استخدام عدة ذات نهاية مسطحة مع□قوس في نهايتها بنصف قطر (٣ ملم)، زاوية الجدار (٥٥ درجة) والسرعة الدورانية للعدة (٨٠٠ دروة بالدقيقة). و□م ايجاد اقل قيمة للإجهادات المتبقية (٢٤,٣٨٩ ميكاباسكال) عند استخدام عدة شبه كروية قطرها (١٢ ملم)، زاوية الجدار (٤٥ درجة) والسرعة الدورانية للعدة (٨٠٠ دروة بالدقيقة).