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Investigation of Deformation Mechanism and Failure Mode in Two Point Incremental Sheet Forming

Harith Yarub Maan[1]
[1] Department of Industrial Management, College of Administration and Economics
University of Baghdad, Baghdad, Iraq
Email: harithmaan@gmail.com

Abstract. In this work, the deformation of material and fracture mechanism during the incremental sheet forming process experimentally investigated. The mechanism of deformation is dependent on the process parameters. The present work experimentally explains how the tool radius, step size, and feed rate affect the failure mode during two-point incremental sheet forming. Experimental work achieved to examine the failure modes and analyses the reasons. The deformation of the material in two-point incremental sheet forming is a compound of stretching, shearing, squeezing and bending of material through a deformation zone. The experimental plan based on eighteen experiments cover all the conditions leading to the appearance of failure. The results showed an increasing tool radius and step size the behaviour of failure changes from crack without previous necking to crack with necking. The result showed four types of failure that were found during the TPIF process and identify the factors that lead to their appearance.

1. Introduction

Incremental sheet forming process (ISF) is a flexible forming technique that has become more focused in the past few years because of the need of industrial applications for a process characterized by high flexibility and low cost and do not need additional complications in the manufacturing process and suitable for the production of small batch, prototype and complex shapes[1,2]. Compared with traditional sheet forming process, ISF is characterized by high formability as well as no need to die and it will be low cost. In this process, the sheet is clamped on a frame and using a hemispherical tool that moves by numerical controlled pre-programmed toolpath on a CNC machine that subjected the sheet to localized plastic deformation at tool-sheet contact zone. Duo to nature of deformation mechanism, improved the formability of the material and deform above the forming limit diagram (FLD) [3]. High levels of deformation can be obtained compared to other conventional processes so many researches have been studies to explain the deformation mechanism, fracture behavior and formability of incremental sheet forming process. The high formability of process has been explained by review of six deformation mechanism: as contact stress; bending under tension; shear effect; cyclic loading effect; geometrical inability and hydrostatic pressure and discussed the difference between the necking and the fracture limit in ISF [4].

Experimental investigation to explain the difference between fracture mechanism including necking before fracture or fracture with suppression of necking have been presented [3]. Analytical model based on membrane analysis with the experimental observation to examine the material failure mode in single point incremental forming presented by M.B. Silva et al [5] Many researchers have focused on the development of the fracture during single point incremental forming (SPIF), so there are still little published research in a TPIF process. Difference toolpath to produced complex shapes with partial die have been investigated by Astubara [6] and found that material deformation follow the sine law. M.B. Silva et al [7] presented experimental and theoretical investigation based on the analytical model for SPIF to explain the difference between the formability in SPIF and TPIF with partial die. B. Lu et. al [8] investigated the Double side incremental forming (DSIF) concept and the fracture failure and material deformation explained based on experimental and membrane stress analysis.

Based on FE analysis D.Y. Seong et al [9] explained the material deformation in SPIF by through-thickness necking analysis and the result showed that the layer has different stress state. A fracture prediction based on a numerical investigation in TPIF by Chenhao Wang [10] the micro-crack closure effect is depend to predict ductile fracture in TPIF with a varying wall angle have been used. SPIF with multiple sheets proposed by C. Raju et al [11] to improve the production rate of a process. Carlos F. G. et al [12] presented FE model to predict fracture and damage in the SPIF process based on extended Gurson model. Most researchers see that deformation is a compound of stretching, shearing and bending of material through a deformation zone that causing localized plastic deformation. The appearance of fracture predicted based on fracture FEA model in SPIF presented by Rajiv Malhotra et al [13] and proposed a theory "noodle" showed that the increasing of the formability due to the behavior of localized deformation and through the thickness shear with local bending play an important role in fracture. Y. Fang et al [14] developed an analytical model for (SPIF) to describe the localized deformation mechanism with strain hardening and bending effect the behavior were considered to analyze the deformation and fracture mechanism. In the present work, the influence of process parameters, the tool radius, step size, and feed rate affect the material deformation and failure mode during TPIF is experimentally investigated.

2. Experimental set-up

A 3- Axis CNC milling machine was utilized to achieve the full die TPIF test based on a z level layer toolpath trajectory. A dome shape is used as test geometry to model the TPIF process with radius of 55 mm. In this test, the wall angle progressively increases with depth. The part was formed by TPIF process until it cracked. A square aluminum sheet (Al 1050) with thickness of 0.9 mm. The initial size of the sheet was 280 x 280 mm. With a commercial CAD/CAM package, the tool path generated. The CAD test model, generated toolpath and set up of experimental tooling is shown in Figure 1. Bearing oil and engine oil used as a mixture of (25% and 75%respectively) was used as a lubricant. The Material properties obtained by a uniaxial tensile test are shown in Table 1. Three process parameters were analysed; step size, feed rate and tool radius as shown Table II. Eighteen experiments were carried out based on information listed in Table 2. Each experiment was conducted three times to confirm the results.

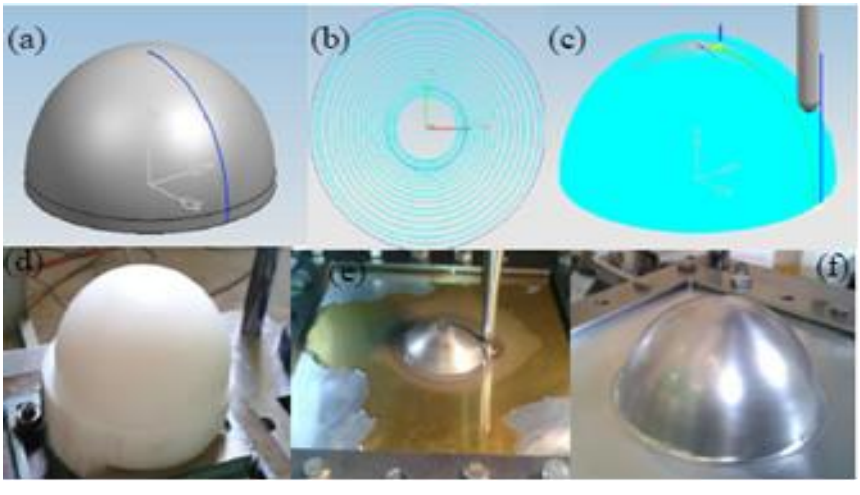

Figure 1. (a) Test geometry of pyramid shape. (b) and (c) Toolpath for dome shape. (d) Full die support, (e) The experimental stages for incremental forming (f) Formed shape.

Table 1. Mechanical properties for Al-1050 sheet.

		Unit
Material	Al-1050	
Tensile strength	105	Mpa
Yield strength	70	Mpa
Elastic modulus	70	Gpa
Poisson's Ratio	0.33	
Density	2700	kg/m3
Total elongation (%)	4	
Max elongation	1.89	mm
Percent elong. at max load (%)	1.5	mm

Table 2. Process parameters employed in this study.

Tool radius (mm)	Step size (mm)	*Feed rate (mm/min)*
5 6	0.3 0.5 0.7	400 600 800

3. Results and discussion

The influence of process parameter of TPIF on deformation of material and failure mechanism have been experimentally studied. In TPIF process, when the tool has touched the sheet during a process, the process of deformation begins, the contact area is small, itis subjected to a concentrated plastic deformation. The deformation zone is subjected to pressure stress, which the support is applied in the opposite direction, which changes the stress state of tensile stress to compression on sheet-die contact, and this behavior leads to the suppression of necking, which improves the formability relative to SPIF. The results of experimental work show that failure occurs outside the deformation zone and is always above the contact area between the tool and the sheet as shown in Figure 2. All cracks that found in TPIF is opening mode and this agreed with previous literature.

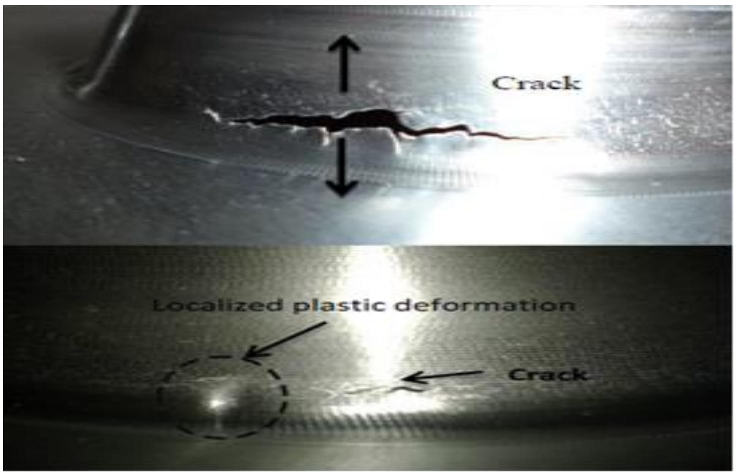

Figure 2. Cracks that occur during TPIF process

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The Bending-under-tension is a true dynamic phenomenon, it only occurs when the material is actually moving around the punch [4] and it found during forming where the material is being bent in contact zone at the minor stress direction and stretched when exit from contact area as shown in Figure 3.

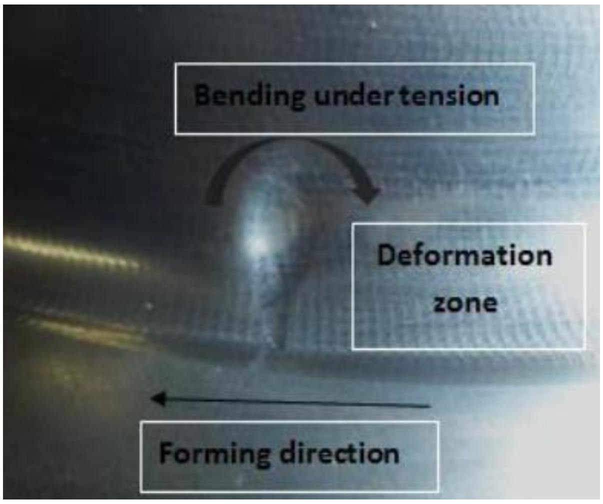

Figure 3. The localized plastic deformation during TPIF process

The localized plastic deformation is small there for preventing a neck to appear, but the strain state reaches during incremental forming at specific levels at fracture limit then crack take place. The neck cannot grow into a crack, since the tool is moving along tool path before the fracture is done, but in experimental test the is neck grow and reach to failure limit with exist tensile stress. The fracture appears in the transition zone between the contact area and the wall of the formed part and its behavior varies according to the changes in the selected process elements. From result shows that there are four types of failure that found during TPIF process; (I) small crack located above the deformation zone;(II) straight crack propagation path; (III) zigzag crack propagation path and (IIII) small cracks are distributed around the circumference of the product as shown in Figure 4.

First type of failure mode (I) takes place at a lower wall angle of part and found and the Failure mode type (II), this type occurs at low feed rate with large tool radius and step size due to the large contact length between the sheet and tool. At this condition the necking was appears and failure by fracture finally with extreme thinning and some wrinkles were found below the fracture. Third failure mode (III) takes place at moderate feed rate (at 600 mm/min) for all tool radius and step size that were used in experimental work. This type of failure occurs with fracture under suppression of necking condition. The failure mode (IIII) appears when used high value of process parameters where the large tool radius and step size increases the contact length and high stretching that found along the deformation zone, also the higher feed rate increases the through thickness shearing and the generated heat that cause sudden failure of product with continuous straight crack propagation path as shown in Figure 5. When the diameter of the tool is large and the step size as well stretching stress will be higher due to increased bending of the sheet around the tool, In addition, the area of the deformation zone increases in the longitudinal direction Thus, force is increasing in this direction. This explains the appearance of wrinkles with the fracture in this region as found in forth type. Noted that there is a necking before failure when the thickness of the formed sheet is small at large wall angle, and this is located at the bottom of the base of the product. The deformation mechanism depends mainly on the contact zone and the amount of deformation in the longitudinal direction is greater than the circumferential direction. In all cases, noted that the fracture occurs in the transition zone on the wall between the contact area (the deformation zone) and the area of non-contact of the product wall. Table 3. Shows the results obtained for all experimental work.

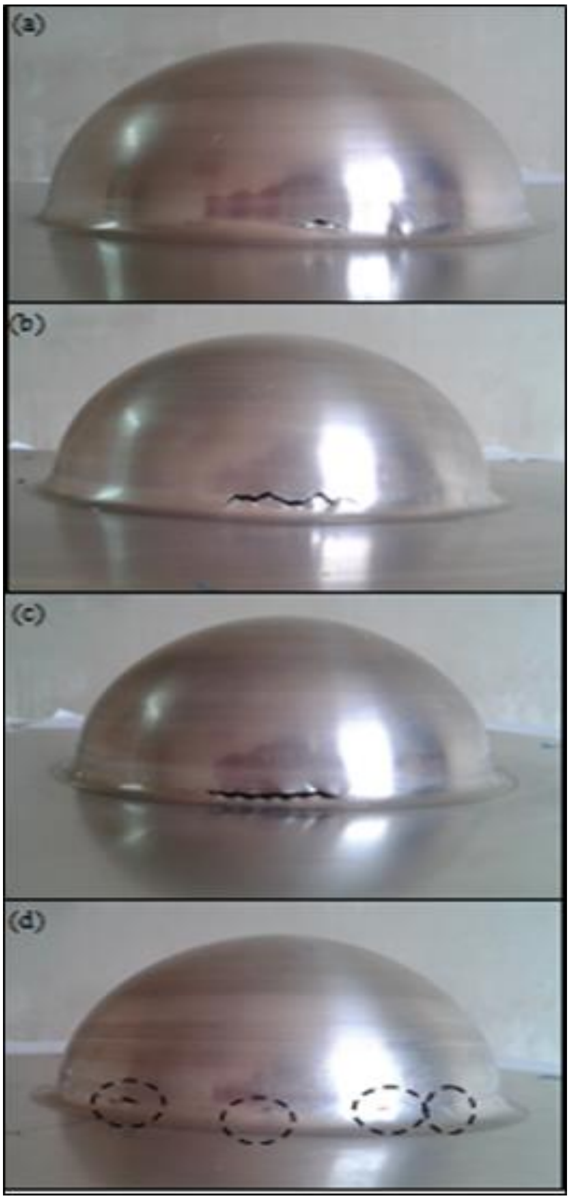

Figure 4. Failure modes in TPIF process

Figure 5. Failure modes in TPIF process with rapid crack

Table 3. Process parameters of the experiments and their output

No.	Tool radius (mm)	Step size (mm)	*Feed rate (mm/min)*	*Failure mode*
1	5	0.3	400	I
2	5	0.3	600	III
3	5	0.3	800	III
4	5	0.5	400	II
5	5	0.5	600	III
6	5	0.5	800	III
7	5	0.7	400	II
8	5	0.7	600	III
9	5	0.7	800	IIII
10	6	0.3	400	II
11	6	0.3	600	III
12	6	0.3	800	IIII
13	6	0.5	400	II
14	6	0.5	600	III
15	6	0.5	800	IIII
16	6	0.7	400	II
17	6	0.7	600	III
18	6	0.7	800	IIII

4. Conclusion

The aim of this study was to increase understanding the deformation of material during TPIF process. The influence of process parameters has been investigated to explain the mechanism of localized deformation and determine the type of failure pattern. The selected experiments cover all the conditions leading to the appearance of failure. The failure appears in the incremental forming process as a fracture. The failure is located at bottom of the part. During forming, the plastic deformation a uniform thinning and then fracture. There is no necking appeared before fracture, but when the tool radius large and high value of step size the necking taken place due to stretch that happened and the failure suddenly. From results of the experimental work concluded that the longitudinal tensile will generate large elongation. Local deformation is responsible for local necking in the contact zone, which increases the deformation and has a high elongation ratio compared to traditional processes. During the formation process, the fracture generated can be controlled by selecting suitable elements and this depends on the deformation of the contact zone. The relationship between process variables and their effect on the conditions of deformation in the contact zone represented by stretching along the wall in the longitudinal direction, through thickness shear, bending and the opposite pressure that subjected by the die from the other side, it changes the behaviour of the fracture during the experiments performed which works to form different types of failure. Four types of failure that found during TPIF process and its affected by process parameters at different levels. Necking is not shown when there is a regular distribution of thickness, especially in the low angle of the wall, but with the increase of the angle of the wall, especially in the vicinity of the base of the product is not subject to the sine law, leading to the emergence of necking before the failure.

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