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THE USE OF 3D ELEMENT ON THE EVALUATION OF THE STRAIN STATE IN AN INCREMENTAL SHEET FORMING

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Abstract. *In order to forming ever more complex components, new manufacturing processes and new alloys have been developed in recent years. One of these processes is called Incremental Sheet Forming (ISF), where a blank is deformed by a small spherical punch, following a predetermined path, until it reaches the desired shape. The lack of expensive dies and presses can provide an economical and competitive alternative for components with low production volumes and high added value. This process has demonstrated great potential for forming complex parts, because the local strain induced by punch reaches levels of drawability much higher those achieved by conventional forming. However, the exact determination of forming limit this process has generated extensive research on the subject. Due to it being a punctual deformation process, the FLC (Forming Limit Curves) applied with reasonable accuracy in conventional stamping, are not applicable to incremental forming process. The most recent results from the literature have shown that the mode of strain that occurs in this type of forming still generates controversy within the scientific community. The purpose of this work was to simulate and evaluate, by Finite Element Methods, an incremental forming process using 3D elements. The knowledge of the strain (plane stress, plane strain or triaxial) that is occurring in the region of plastic deformation will be crucial to developing a theory of failure most appropriate for this process.*

Keywords: *SPIF, Stress, Strain, FEM*

1. INTRODUCTION

The idea of forming a part incrementally, starts with Leszak in 1967, but only be developed with the creation of numerical computer control machines, CNC (Sena *et. al*, 2011). The studies about incremental forming started at academic form in the 90s in Japan and later extended to Europe and Canada (Jackson, K. *et al*, 2008). Patrick (2011) reports that up to half of the 2000s, studies were based on experimental cases, and the theoretical studies on the subject are more recent.

An understanding of stress and strain in conventional stamping (where a punch forms a plate, called blank until that take the form of a matrix) is now reasonably grounded by several studies in the literature, performed for many years. In conventional stamping the predominates process is a plane stress, where there is no stress variation along its thickness. Already with incremental stamping, this forming process is not clear, for lack of more focused studies on this subject and sometimes even a lack of ways that can assist the study. The understanding of what occurs over the blank thickness is an importance parameter for describing the state of stress / strain which occurs during the forming process, which makes it difficult this perception in practice. Figure 01 shows a schematic of a conventional stamping process.

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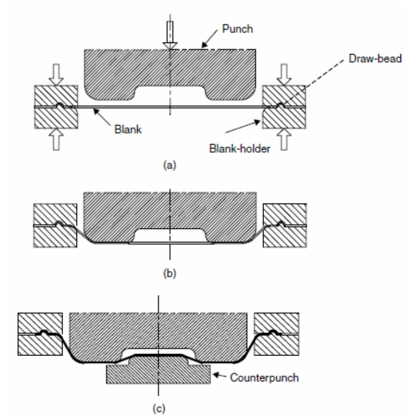

Figure 01: Conventional Stamping a) blank and tools position b) punch acting on the blank, c) contact between blank and die (Marciniak *et al*, 2002)

The incremental sheet forming can be defined where one sheet is plastically forming through a tool with a trajectory predetermined (Bertoli *et al*, 2012). According to Allwood *et. al*, (2005) the incremental stamping has some variations defined as (Figure 02):

- Single point incremental forming
- Double point incremental forming
- With negative die
- With positive die

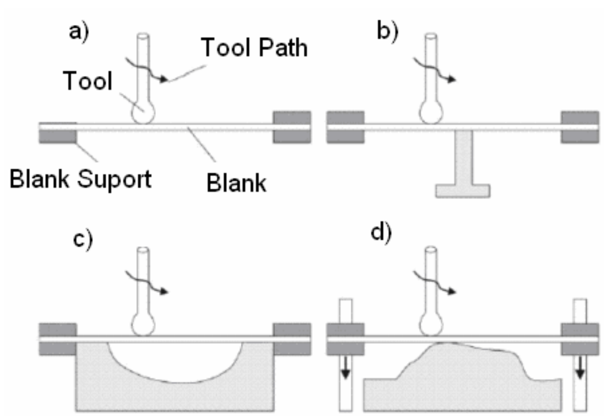

Figure 02. Kinds of Incremental Stamping a) Single point incremental forming; b) double point incremental forming; c) with negative die; d) with positive die (Castelan, 2007)

This is a low cost process (compared to other forming processes), with increasing application of rapid prototyping in metals, biomechanics and small batch production parts. Current studies focus on the experimental and numerical analysis (Marabout *et al*, 2011). Comparing the incremental stamping process with conventional stamping, it has the incremental stamping process achieves deformations much larger than the conventional (Salah *et a*l, 2011), it is a process that can be used to deep and complex parts forming. The incremental stamping process by single point (Figure 03) where there is only one tool, dispensing the dedicated die, is the a lower cost process than others incremental process, with greater simplicity of running, making it the most studied process (Petek *et al*, 2009).

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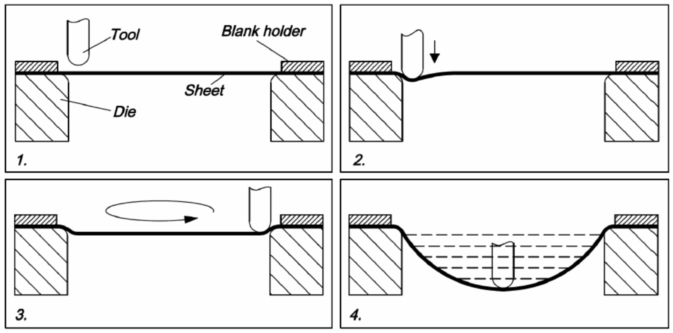

Figure 03. Single point incremental forming scheme (Kim, 2000, cited in Pohlak, 2007)

The finite element numerical simulation (FEM), has been widely used in various industrial segments, with this method can be anticipate the physical tests results and also study details of models that can hardly be studied in physical parts, or lack of technology or high costs related to instrumentation.

The use of numerical simulation tools, especially those using the finite element method, has wide acceptance in the field of mechanical engineering. With the evolution of computers with increasingly powerful processors, enables the simulation with greater detail, using more complex models and boundary conditions with the largest representation with reality.

The present study aims to understand through numerical simulation what occurs in the field of strain and stress along the thickness of a part forming to the incremental stamping process by single point. A numerical finite element model with 3D elements, was used to elucidate the theoretical basis.

2. MECHANINCAL OF SHEET FORMING

The conventional stamping process can be describe like Figure 04 below.

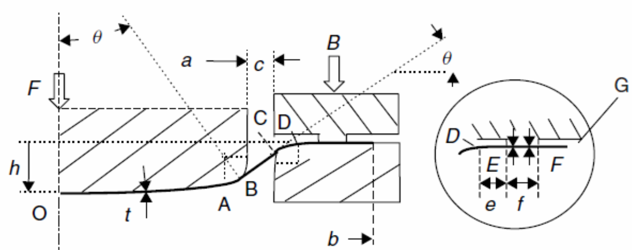

Figure 04: Conventional stamping process (Marciniak *et a*l, 2002)

Where:

a: punch semi-width
b: blank semi-width
c: Clearance between punch and die
e: land width
f: widht of frictional clamping
h: punch penetration
t: blank thickness

Considering only the fixing blank is made by blank-holder friction, can see at any time of the stamping process, at a given depth h, the zones found in Figure 04:

OB – material in contact with the punch
BC – unsupported sheet in the side wall
CD – blank in contact with the die corner radius
DE – blank on the die land without contact pressure
EF – material about fixing blank-holder
FG – blank free material

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Assuming that the region of the blank from the center O to the edge F, are deformed plastically (fact that does not happen, because there are areas that are just moving with the punch force), the center O to the tangent B, the blank is being stretched and slipping out of the center O and the frictional forces are acting to contain this slip in the center. From the initial point of contact with the die C to point F, the blank tends to slide to the center and the frictional forces tend to hold the same.

3. METHODOLOGY:

To check the stress and subsequent comparison of their behavior along the thickness, two numerical finite elements models are created, for the simulation of conventional stamping and another for incremental stamping.

The implicit nonlinear formulation was used for both models on the commercial software Abaqus ®, which has good formulation when using contact interactions and large geometric deformations. The blank is built with 3D elements, mostly consisting of 8 nodes (hexahedra). The blank thickness was composed of a 3-layer elements, to better represent the effects of stress in this sense, was considered non-linearity of material with the addition of plastic curve. Figure 05 shows the used element as well as its position along the thickness.

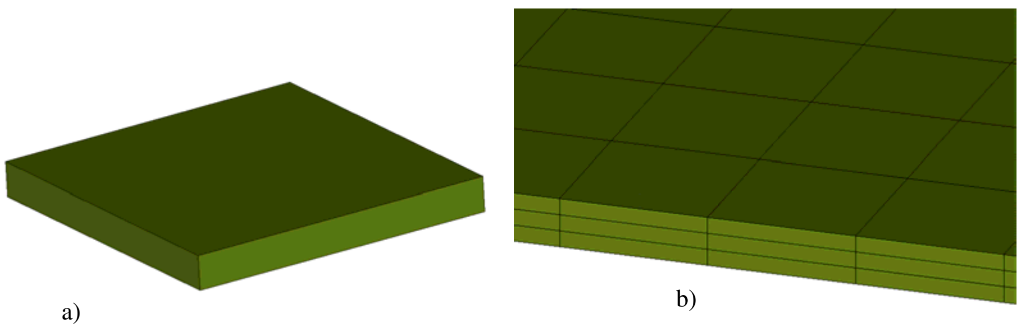

Figure 05: FEM Model a) 8 nodes elements, b) Elements configuration along the thickness

For to the punch (conventional stamping) and for rotary tool forming (incremental stamping), were used 2D elements with infinite stiffness. Figures 06 and 07 present the complete used finite element models..

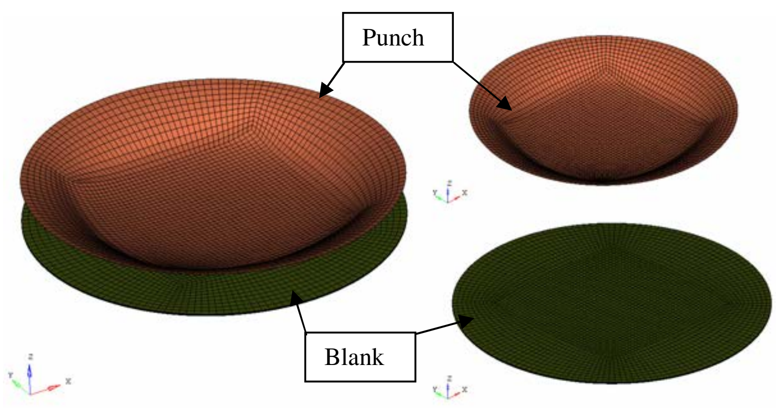

Figure 06: Conventional Stamping Model

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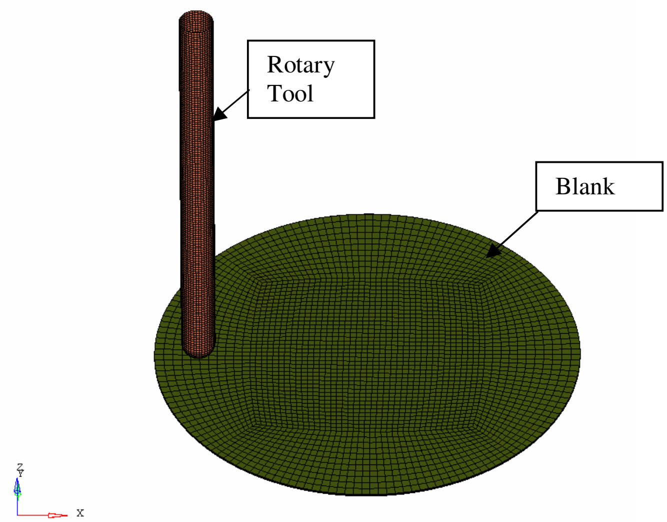

Figure 07: Incremental Stamping Model

The numerical analysis, for conventional stamping, consisting in imposing a displacement of the punch against a blank, through which a contact model, deforms the blank and the same is restricted in all of its edge, simulating the die.

The incremental stamping model, consisted of a 12mm diameter tool, which goes forming the blank with circular motion and increments towards to the center and down of the blank, it was also restricted to the blank edge.

4. RESULTS:

4.1 Numerical results:

At the end of the numerical analysis, the stresses and strains results were extracted along the thickness, to see what happens when a blank is forming by conventional stamping and incremental stamping. The following figures describe the results of conventional and incremental stamping. The analysis was performed as follows.

The Figures 08 and 09 show the deformed blank forming by conventional and incremental stamping respectively, with the values of stress σ_{xx} and σ_{yy}, the measuring point of stress lies in the maximum contact region between the punch / tool and the blank.

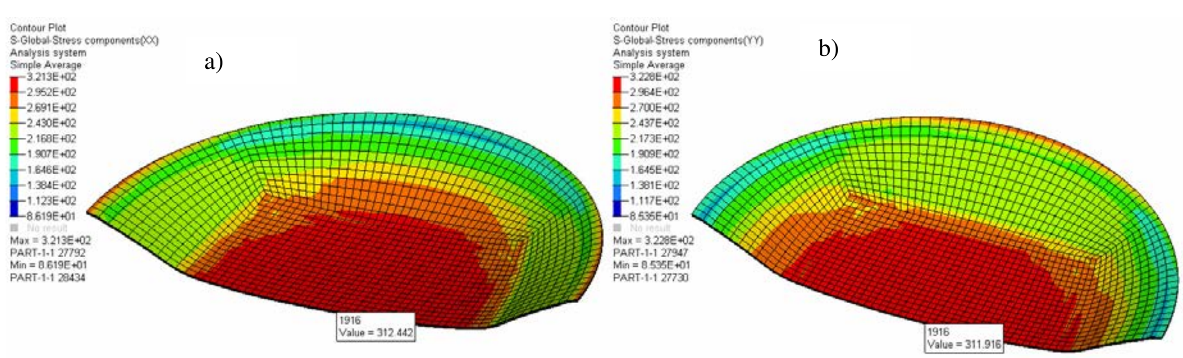

Figure 08: Conventional Stamping a) σ_{xx} = 312.442 MPa, b) σ_{yy} = 311.916 MPa

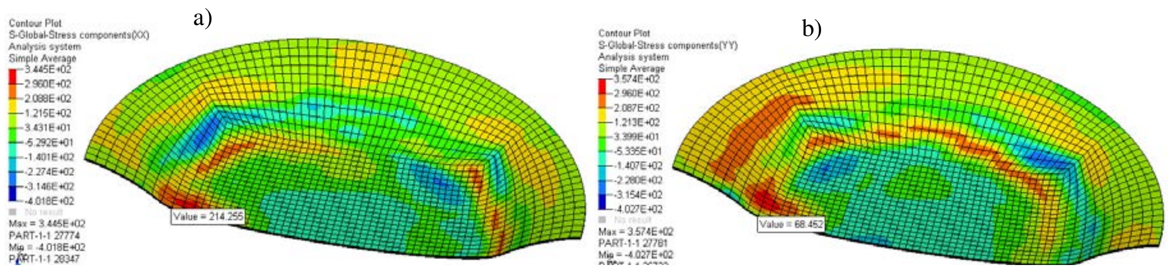

Figure 09: Incremental Stamping a) σ_{xx} = 214.255 MPa, b) σ_{yy} = 68.452 MPa

For the conventional stamping, the stress components was measuring on the blank central point, as show in Table 01, which shows the stress variation in thickness, on superior and inferior section. It is observed that the values do not suffer major changes until the curvature beginning (red region in Figure 10). After the curvature start, the stress values are different, but the behavior along the thickness is the same of central point, ie the stress value does not change considerably over thickness and is in a smaller proportion than stress values for the other senses.

Table 1. Stress on conventional forming sheet

Measurement Points	Stress		
	XX (MPa)	YY (MPa)	ZZ (MPa)
Point on Superior Thickness	312	311	-0.55
Point on Inferior Thickness	314	313	-0.03

According to Marciniak *et. al* (2002) to justify applying a stress plane state, it has the following characteristics:

1 - The punch curvature radius has be much greater than the thickness of the blank being deformed;
2 - The punch corner radius should be 5 to 10 times larger than the thickness;
3 - The main stress must not exceed 15% higher than the effective stress, this confirms that the contact pressure exerts little influence on the process.

All this description is valid that there are no little radius in forming tool, which does not occur in conventional stamping. For incremental stamping, the process is fully loaded with a punctual pressure force of great intensity during the forming process, because at the time that the tool comes into contact with the blank, there is only a small point in contact with the same , and the blank thickness may be greater than the punch curvature radius.

Was check the results of stresses for incremental stamping in order to do a comparison of the behavior between conventional and incremental stamping.

The incremental stamping measurement point was the last increment moment of the tool on the blank, because, unlike the conventional stamping, the forming tool, comes into contact with blank at several different points at different times. Table 02 shows the stress variation in thickness between the top and bottom section.

Table 2. Stress on incremental forming sheet

Measurement Points	Stress		
	XX (MPa)	YY (MPa)	ZZ (MPa)
Point on Superior Thickness	214	68	-57
Point on Inferior Thickness	325	338	43

In order to evaluate the stress and strain distribution along the thickness, were selected four consecutive nodes (here called points), as shown in Figure 10.

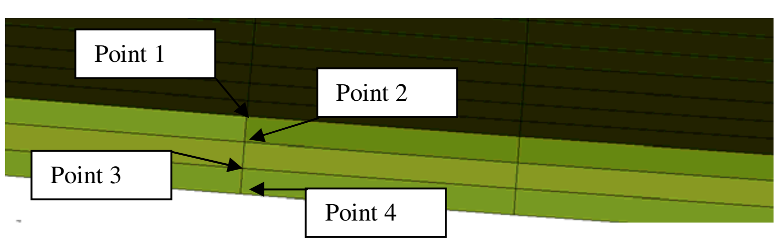

Figure 10: Stress measurement points

Figures 11 and 12 show graphs with the stress variations in the thicknesses of incremental and conventional stamping processes. As shown in the previous tables, we can see a difference in behavior of the stress variation across the thickness. The conventional stamping not has that significant variation in the points thickness, which is already expected because it is a plane stress behavior, which can not be said for the incremental sheet metal forming.

The incremental stamping graph behaves quite different from conventional stamping, there is considerable stress variation along the thickness in the three principal directions, XX, YY and ZZ.

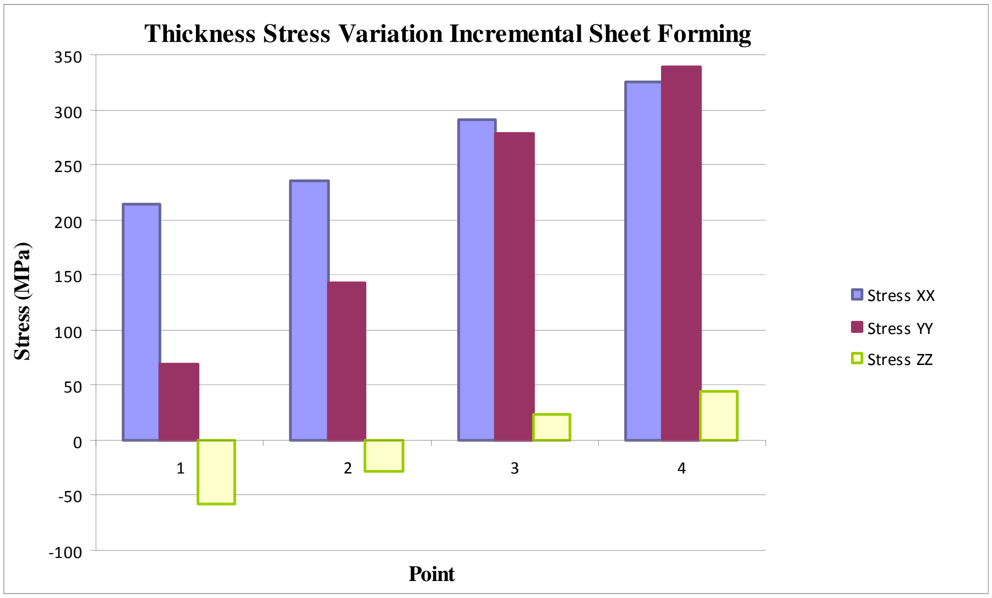

Figure 11: Stress variation along thickness in Incremental Stamping

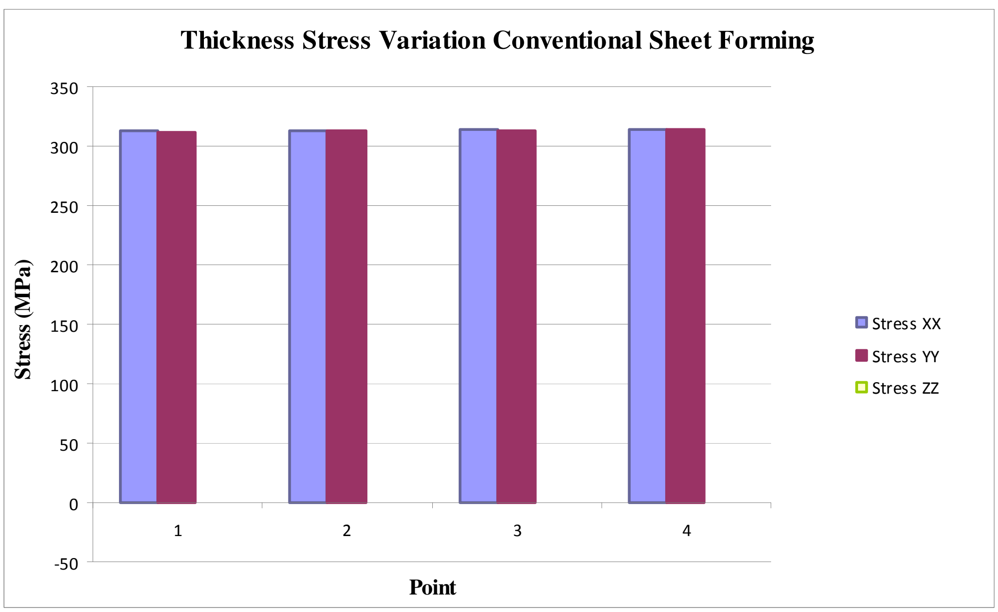

Figure 12: Stress variation along thickness in Conventional Stamping

For the same points, were analyzed the strain components along the thickness for the conventional and incremental process according shows the Figure 13 and 14. For the conventional stamping, it can be observed the same intensity strains in directions XX and YY and a higher value in ZZ direction, as was expected in the literature. Incremental stamping showed a different behavior, which have different strain values in 3 main directions.

These results show that the incremental printing does not fall in the plane stress (a characteristic of the conventional stamping), or in plane strain, during the contact between the spherical punch with the blank. The stress state at the time of plastic deformation is characterized by a triaxial stress state.

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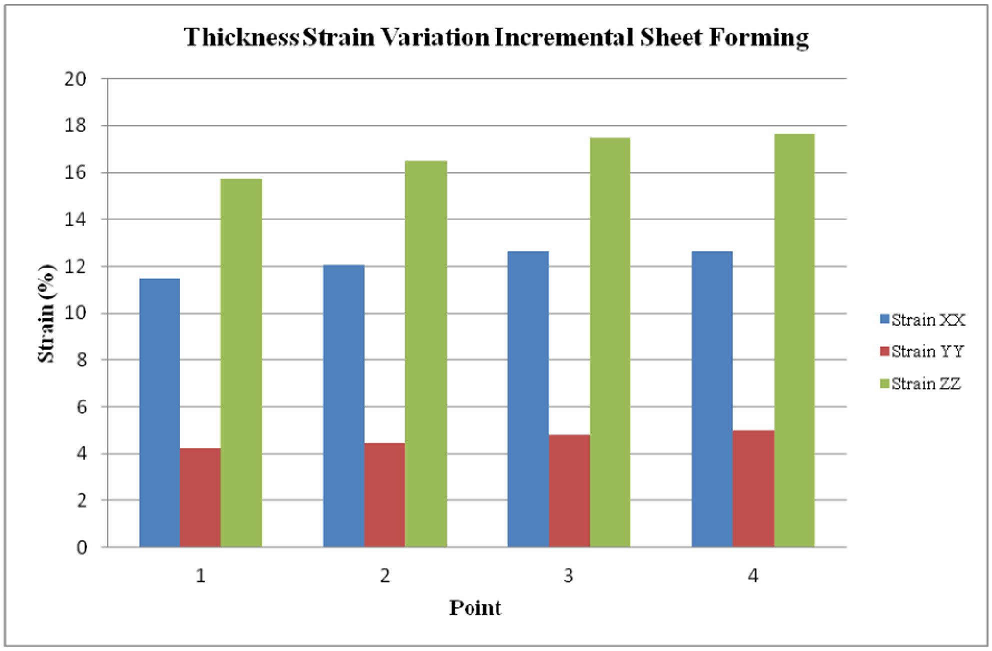

Figure 13: Strain variation along thickness in Incremental Stamping

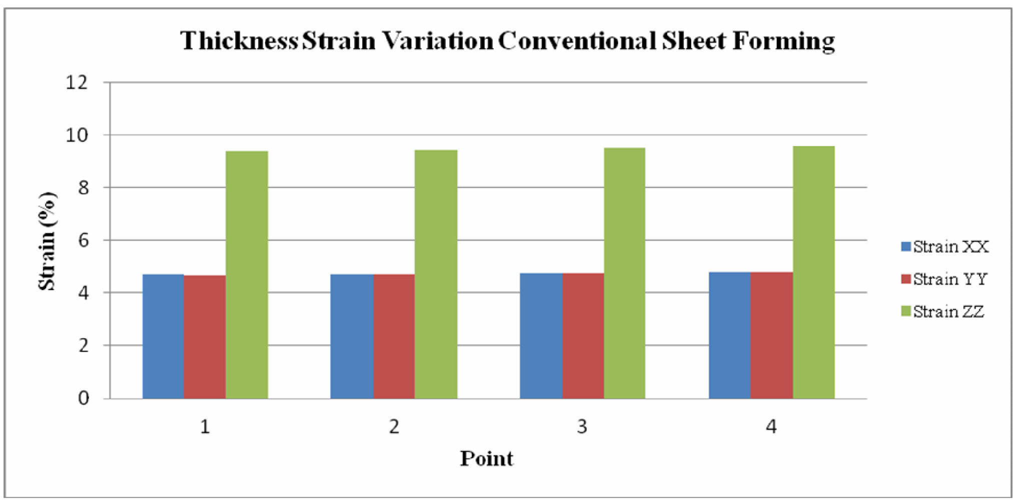

Figure 14: Stress variation along thickness in Conventional Stamping

4.2 Analytical results comparison:

As reported in the present work, the understanding of the field of stress and strain for the conventional stamping is well established, therefore, can run a comparison between the results of the numerical model and the analytical formulation for prove this theory.

The following is a brief description of the analytical behavior of the stress and strain fields in a conventional stamping under plane stress.

Generally the principal strain $\varepsilon_1;\varepsilon_2;\varepsilon_3$ can be given by:

$$\varepsilon_1 = \ln\frac{d_1}{d_0};$$
$$\varepsilon_2 = \ln\frac{d_2}{d_0}; \qquad (1)$$
$$\varepsilon_3 = \ln\frac{t}{t_0};$$

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However, there is a ratio between the strains, named β which is given by:

$$\beta = \frac{\varepsilon_2}{\varepsilon_1} = \frac{\ln(d_2/d_0)}{\ln(d_1/d_0)} \tag{2}$$

Replacing the Eq (2) in Eq. (1), has:

$$\begin{aligned} &\varepsilon_1; \\ &\varepsilon_2 = \beta\varepsilon_1 \\ &\varepsilon_3 = -(1+\beta)\varepsilon_1 = -\varepsilon_1 \end{aligned} \tag{3}$$

The effective strain is given by:

$$\varepsilon_{efe} = (\sqrt{\frac{4}{3}(1+\beta+\beta^2)})\varepsilon_1 \tag{4}$$

In the conventional stamping process can be considered that in the contact region between blank and punch there is a stress plane state, ie there is no stress variation along the thickness. Thus the principal stress values $\sigma_1;\sigma_2;\sigma_3$, associated with the stress ratio factor α can be given by:

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

$$\sigma_1; \quad \sigma_2 = \alpha\sigma_1; \quad \sigma_3 = 0 \tag{6}$$

The effective stress is:

$$\sigma_{efe} = (\sqrt{1-\alpha+\alpha^2})\sigma_1 \tag{7}$$

And the thickness on the deformed region is:

$$t = t_0 \exp[-(1+\beta)\varepsilon_1 \tag{8}$$

With the formulation above, the analytical results for the conventional stamping are show in Table 03, and are compared with the finite element model results.

Table 03: Comparison Conventional Stamping, Analytical results and FEM results

Analysis	Results				
	σ_1	σ_2	ε_1	ε_2	Final Thickness
Analytical	321.73 MPa	315.46 MPa	0.0488	0.046	0.6366 mm
Numeric	312.44 MPa	311.92 MPa	0.047	0.0468	0.6362 mm
Difference	2.97 %	1.13 %	3.83 %	1.71 %	0.006%

The major difference on the results was of 3.83% and can be considerable negligible, so the plane stress theory is acceptable for a conventional stamping

The same analysis was performed for the incremental stamping and the results are showing on the Table 04.

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Table 04: Comparison Incremental Stamping, Analytical results and FEM results

Analysis	Results				
	σ_1	σ_2	ε_1	ε_2	Final Thickness
Analytical	378.26 MPa	321.17 MPa	0.094	0.057	0.601 mm
Numeric	214.26 MPa	68.45 MPa	0.1149	0.042	0.555 mm
Difference	76.54 %	369.2 %	22.11 %	35.71 %	8.29 %

The Table 04, show that the difference between numerical and analytical models, for incremental stamping is so large, so the plane stress state suppose can't be used for incremental process.

5. CONCLUSIONS:

As can be seen from the data presented, the stress field model of conventional stamping, behaved as expected, confirming that the predominant state in a conventional stamping plate is plane stress. It is in this case the stress that does not vary along the thickness and the ZZ principal stress direction is much lower than other planes.

The same can not be said for the incremental stamping process, which showed considerable stresses variation along the thickness, that due to the your punch shape, a punctual tool, which prints a localized load in a small region, thus acting as an indentation and generating the stress fields presented in this work, ie a triaxial stress and strain states.

These preliminary results show the need an incremental forming process further study, having seen the results of this article that you can not use the same deformation mechanism of conventional stamping. From the understanding of the stress and strain states acting on the contact punch area with the blank will be possible to define a more appropriate damage model to the present case, estimating more precisely the each variable limits involved in this process.

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