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Experimental Studies and FEM Analysis Regarding the Influence of Geometric Parameters on Strain, Thickness Reduction and Forces in Incremental Forming Process

The purpose of this study was to investigate the influence of geometrical parameters on the distribution of the principal strains and relative thinning and determination of forces in two directions in single point incremental forming process. For this purpose we have chosen a straight grove piece type. The parameters were taken into account are the punch diameter and step down in z direction. Were conducted the tests on two thickness sheet metal of the same material but having different mechanical characteristics. To determine the distribution of strains we used an optical method and to determine the forces a dynamometer was used. We have made two types of FEM analyses, one to determine the strains distribution and another to determine the forces.

Keywords: *single point incremental forming, experimental research, strain measurement, force measurement, FEM analysis*

1. Introduction

In the last years, many sheet metal forming process have been studied, like laser forming [4], water assisted forming [1] hammering with robots [2] or incremental sheet forming with a small intender. All this forming processes are characterized by a high flexibility and are very suitable for small quantity production and for rapid prototyping applications [3]. The most studied process is incremental sheet forming (ISF) with a small intender. There are two types of incremental sheet forming with a small punch, single point incremental forming (SPIF), which use a single punch and two points incremental forming (TPIF which use besides the small punch a male or female die, a support post or a second intender. In both cases the tool follows a 3D path described by a CNC program.

This metal forming process produces small plastic deformations in the area under the punch. This process is very flexible because for a new part it is enough to change the CAM program and it doesn't need dedicated tools, like deep drawing or stamping.

The latest research in the area includes studies investigating the possibility to form new materials through ISF, like: sandwich panels, which have ductile and largely incompressible cores [8], tailored blanks produced by friction stir welding [5] or polymer sheet components [11]. Other research directions are the optimization of tool path in two points incremental forming [10], to increase the geometrical accuracy of the parts by using an offline model derived from an online sensors-based strategy [7] or to investigate the suitable tool and lubricant for pure titanium sheet [9]. There is also researches that used multi-step tool path to obtain parts with vertical walls having 90° [6] or to investigate hybrid processes, a combination of ISF with stretch forming.

This study aims to determine the influence of geometrical parameters (punch diameter and step) on material strain and thickness reduction distribution and forces in two directions.

2. Experimental tests

2.1. Production of parts

For practical realization of single point incremental forming samples was used a DMG Veco 635 CNC milling machine. Forming equipment was installed on the CNC machine as can be seen in figure 1 a. It is composed of a bottom plate on which there are two brackets that support the die, a die and a retaining ring.

In order to measure forces in two directions (vertical advance direction z and a direction in the plane of sheet x), under forming equipment was installed a dynamometer. Dies have various shapes such as circular, square, triangular and other. To produce the straight groove pieces were used a square die with inside side of 60 mm and 6 mm rounding radii. We used two types of punches one with 6 mm diameter and another with a diameter of 10 mm.

For the punch travel in z direction two steps were used: 0.25 mm and 1 mm. To move the punch was used a feed rate of 240 mm / min with a rotary of the punch 180 rpm. To reduce friction at the contact between the punch and the material, forming lubricant was used.

The material chosen for the production of parts is AA6016 aluminum, having two thicknesses 1.14 mm and 0.8 mm. The mechanical characteristics of the two types of sheets were determined on a tensile test machine Roell RKM & Korthaus 100/20. The obtained data are presented in table 1. These blanks used during testing are cut into squares of 120mm side length.

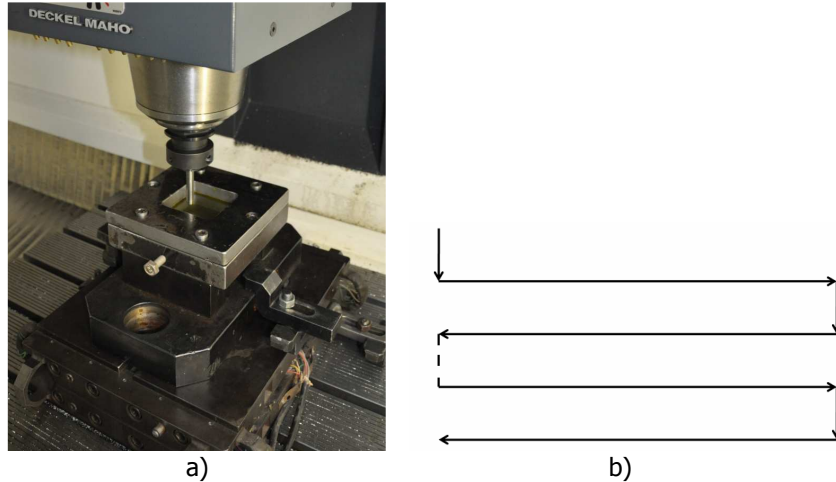


Figure 1. a) Experimental equipment used for SPIF and b) punch trajectories

Table 1.

Thickness [mm]	K [Mpa]	n	ϵ_{ii} [%]	R_{00}	R_{45}	R_{90}
0,8	447	0,207	27,34	0,711	0,457	0,473
1,14	455	0,194	27,35	0,777	0,499	0,729

2.2. Force measurement

Forces were measured using the dynamometer installed under deformation equipment. Were taken from the dynamometer the signals of strain gauge stamps, which were mounted on its rings and through a tool developed in Matlab program tensions were converted into forces. Before this the dynamometer was calibrated to determine the dependent relationship between strain gauge stamps voltage and some calibrated weights. Signal acquisition frequency was 100 samples / sec.

To determine the forces in single point incremental deformation process of straight groove parts was made a set of eight separated pieces, 4 for each thickness of material. Punch trajectory can be seen in figure 1 b.

Punch penetrates with a vertical step of 0.25 or 1 mm in z direction and then moves with a distance of 40 mm in x direction. When the punch reach the end gets a step down into direction z and then moves back with 40 mm in x direction. All pieces have 6 mm height. In table 2 are presented the data.

As can be seen from the table with increasing punch diameter increases x and z forces. With increasing vertical step increases both forces. In figure 2 it can be seen the forces on the two directions.

Table 2.

Code	t [mm]	dp [mm]	pz [mm]	Fxmax [N]	Fzmax [N]
A1	6	0,25	0,8	189,9	653,5
A2	6	0,25	1,14	339,7	1173
A3	6	1	0,8	288,4	908,6
A4	6	1	1,14	472,7	1528
A5	10	0,25	0,8	239,5	891
A6	10	0,25	1,14	386	1533
A7	10	1	0,8	302,8	1163
A8	10	1	1,14	483,7	1908

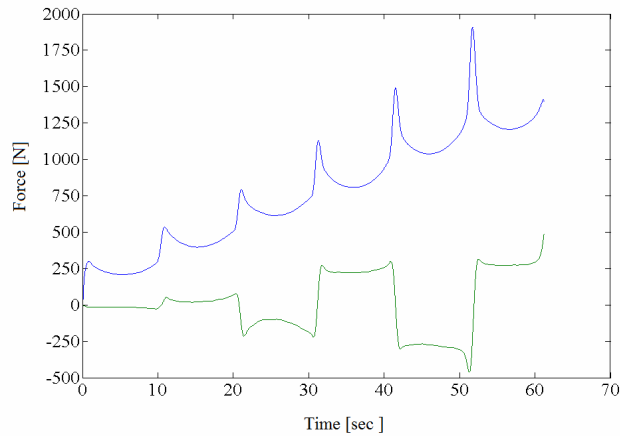


Figure 2. Forces for straight groove parts for case A8 (10 mm punch diameter, 1.14 material thickness and 1 mm vertical step)

Increasing the punch diameter increases the z force. This phenomenon is due to increased contact surface between the die and material. Forces increase with increasing pitch because punch penetrates deeper into the material which increases the contact surface. From figure 2 it can be seen that the form of forces during a linear x trajectory is the same, but as the punch penetrates deeper into the material force peaks are getting higher. From the figure 2 we can see that between two z penetrations the forces are lower in the middle of sheet metal.

The best cases for forces are case A1 for material with 0.8 mm thickness and A2 for material with 1.14 mm thickness. In both cases we have a punch with 6 mm diameter and a vertical step of 0.25 mm. The highest values are obtain in cases A7 for the material with 0.8 mm thickness and A8 for the material with 1.14 mm

thickness. In both cases we have a punch with 10mm diameter and a vertical step of 1 mm.

2.3. Strain measurement

To measure the strains the blanks were marked using a laser deflection before deformation. We used a network of points with a diameter of 1 mm and 3 mm distance between points as can see in figure 3. The grid was made on the part that does not come in contact with the punch. For the strains measurement an optical system ARGUS was used produced by the company GOM. Deformations were measured with a camera with 12mm focal length lens. The pieces were placed on a rotating table. On the pieces we have been placed four encoded bars and 12 markers that allow the calibration of optical system. After calibration pieces are measured by the achievement of a set of 20-24 images. To capture these images the camera is positioned perpendicular to the table, capturing is realized by turning the table with 15 - 20 degrees. Then the camera is positioned at an angle of 45 degrees from the part plane and a set of images is captured by turning the table with 15 - 20 degrees.

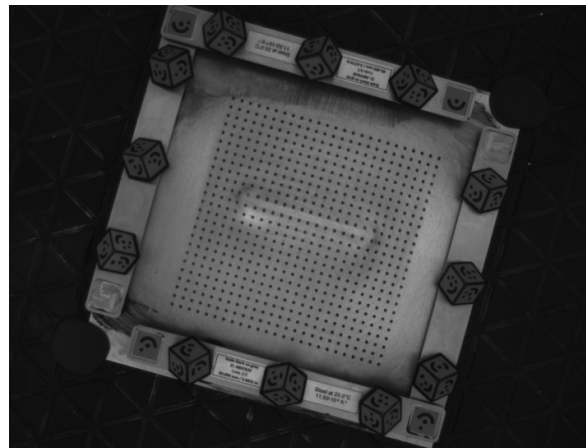


Figure 3. part with coded bars and markers for optic analysis

The program which equipped the optical analyzer can measure deformations and thickness reduction in three ways: conventional strains, logarithmic strains and Green strains. In this paper were presented logarithmic strains.

To determine the relative distribution of strains and thinning have been carried out a set of eight separate pieces, 4 for each material thickness. Punch trajectory can be seen in figure 1 b.

The punch trajectories are the same with those we use for determination of relative strains and thinning. In table 3 are the results of tests.

Table 3.

Code	dp [mm]	t [mm]	Δp_z [mm]	$\varepsilon_1 \max$ [%]	$\varepsilon_2 \max$ [%]	VM [%]	th [%]
B1	6	0,8	0,25	0,175	0,138	0,386	0,374
B2	6	0,8	1	0,18	0,1014	0,369	0,358
B3	6	1,14	0,25	0,221	0,137	0,365	0,366
B4	6	1,14	1	0,231	0,1196	0,344	0,341
B5	10	0,8	0,25	0,17	0,125	0,324	0,312
B6	10	0,8	1	0,177	0,095	0,318	0,305
B7	10	1,14	0,25	0,2086	0,123	0,306	0,298
B8	10	1,14	1	0,212	0,108	0,28	0,306

As can be seen from the table the deformations and relative thinning have the same variation. With decreasing punch diameter for both sheet metal thicknesses major, minor and von Mises strains and thickness reduction becoming higher. With increasing vertical step major strains become higher, but minor strains, von Mises strains and thickness reduction become lower.

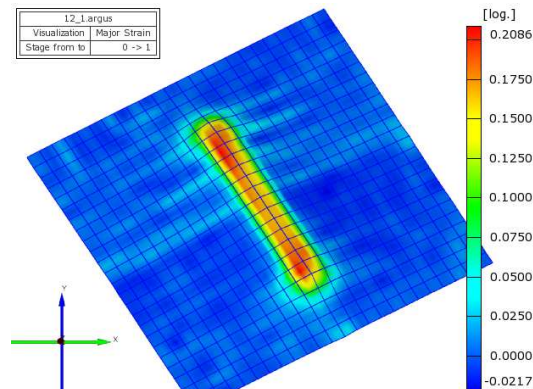


Figure 4. Major strains distribution for straight groove parts for case B7 (10mm punch diameter, 1.14 material thickness and 0.25mm vertical step)

The worst cases in terms of major strains are B2 for 0.8 mm material and B4 for 1.14 mm material and in terms of minor strains von Mises strains and thickness reduction are the cases B1 for 0.8 mm material and B3 for 1.14 mm material. Most favorable cases in terms of major strains are cases B5 for 0.8 mm material and B7 for 1.14 mm material and for minor strains, von Mises strains and

thickness reduction are cases B6 for 0.8 mm material and B8 for 1.14 mm material.

Main strains have maximum values along punch displacement in the x direction, with a maximum in the initial penetration in the z direction. In figure 4 are the main strains and their mode of variation.

Secondary deformations have a maximum in punch penetration areas with a maximum in the initial punch penetration as can be seen in figure 5. In figure 6 can be observed von Mises equivalent strains, which reach a maximum in the punch penetration area and fall in value to the center of the part.

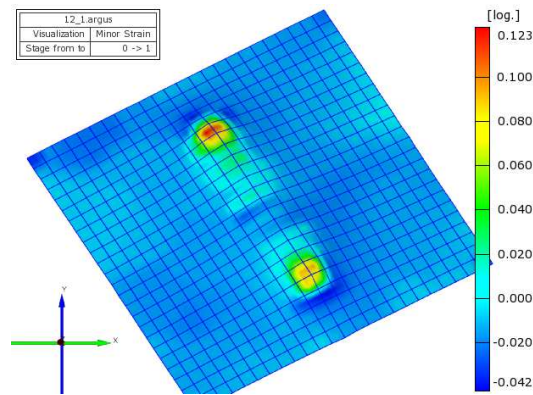


Figure 5. Minor strains distribution for straight groove parts for case B7 (10mm punch diameter, 1.14 material thickness and 0.25mm vertical step)

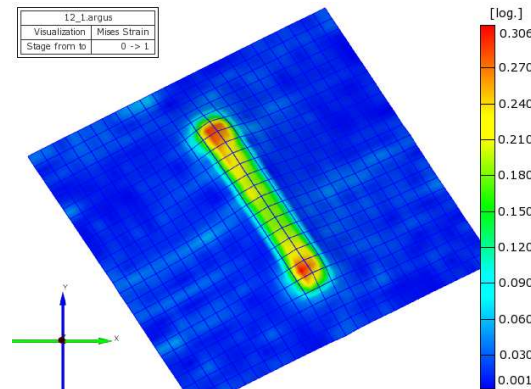


Figure 6. von Mises equivalent strains for case B7 (10mm punch diameter, 1.14 material thickness and 0.25mm vertical step)

In figure 7 is presented the relative thinning in five parallel planes, which are perpendicular to xOy plane and intersecting the points of the part where the punch

penetrates in z direction the blanks. These planes have equal distance between them of 0.1 mm. As can be seen from the graph thinning is greatest in areas of punch penetration.

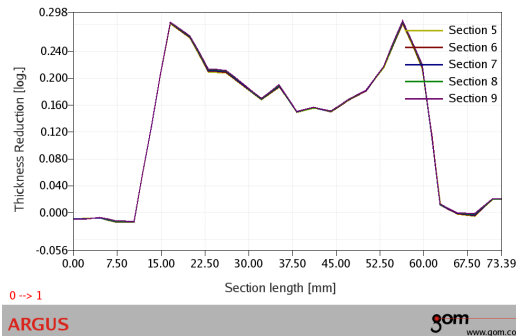


Figure 7. Thickness reduction in a plane perpendicular on xOy plane for case B7 (10mm punch diameter, 1.14 material thickness and 0.25mm vertical step)

4. FEM analysis

In addition to experimental research we conducted two types of finite element analysis. One with a mesh equal with the distance between the grid point used for strains measurement and one with a fine mesh to measure the forces.

For this we use the software LS-DYNA, general-purpose finite element software for analyzing the large deformation response of the structures.

For material model we used an anisotropic elasto-plastic model definition: 3 Parameter Barlat.

4.1 FEM analysis for strains determination

The part, discretized as a shell, deformable body, is composed of 1600 Thin-Shell-163-type elements. A shear factor of 5/6 and a total of 7 integration points through the thickness were used in order to catch the variation of the stresses and strains through the thickness. The material associated with the part's elements is presented in table 1. In figures 8, 9, 10, 11 analysis results are presented for the case B7 of the table 3. As can be seen from the figures the main deformation, thinning and equivalent von Mises deformation have the same relative variation, the results are very close to those obtained experimentally. We compared the strains at the surface of the part because the optical measurement system Argus can measure strains at the surface of the parts. The resulted strains from the FEM analyses are the logarithmic strains as in the real case, strains obtained from optical measurement.

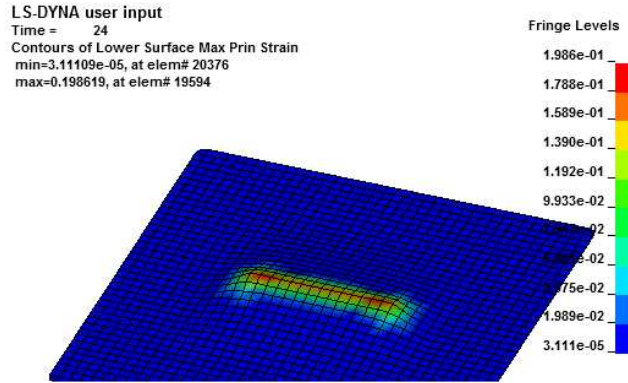


Figure 8. FEM major strains distribution for straight groove parts

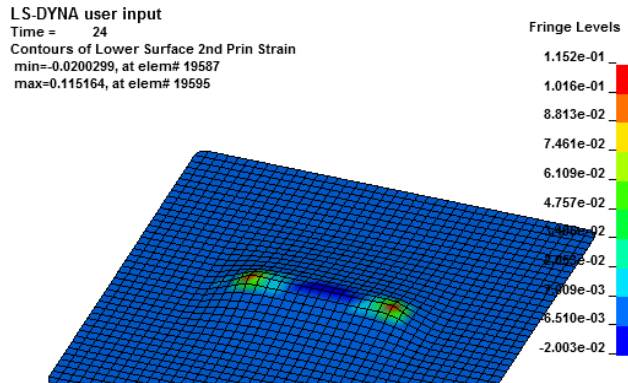


Figure 9. FEM minor strains distribution for straight groove parts

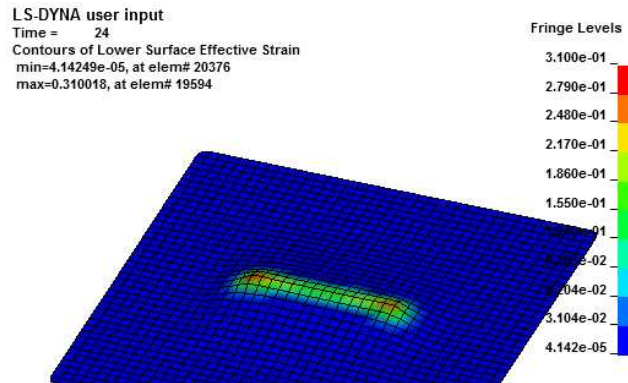


Figure 10. FEM von Mises equivalent strains

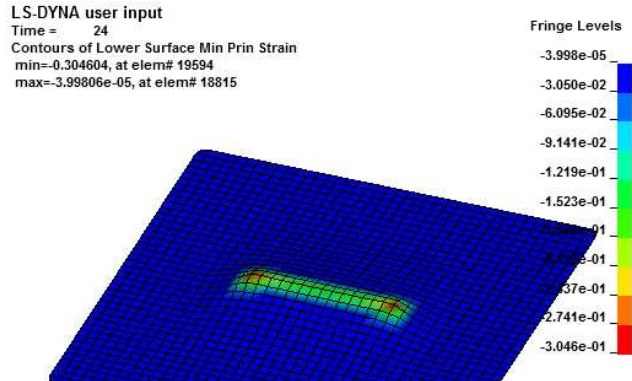


Figure 11. FEM thickness reduction

4.2 FEM analysis for forces determination

The FEM model is the same as for the determination of strains, except that the material was discretized into a very fine mesh. It has 57600 shell elements. In figure are presented the forces for the case A8 from table 2. The results are in very good agreement with those obtained experimentally for both forces.

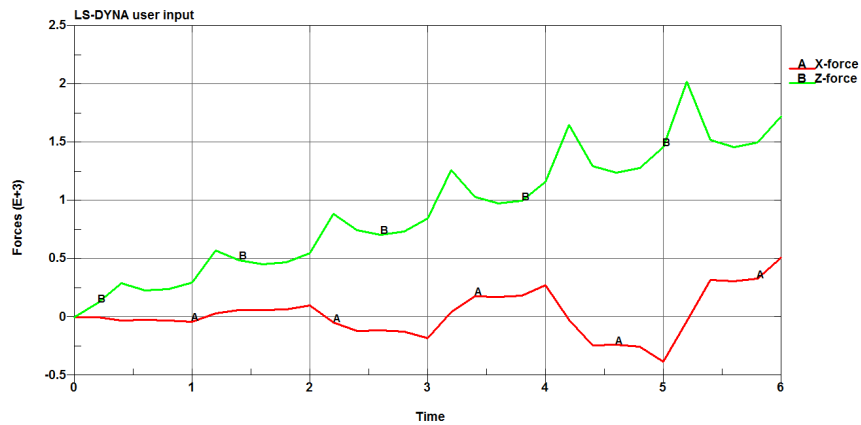


Figure 12. FEM forces in x and z direction

5. Conclusions

After experimental tests and FEM analyses can draw the following conclusions:

The most influential factor when determining the strains and relative thinning is punch, the smaller is it, larger and localized the deformations are. Step down of punch increases the major strains, but lowers the minor strains, von Mises strains and relative thinning values with its growth.

In the case of forces determining the most influential factor to consider is the increased value of step by z axis. As the step is greater forces are greater. Punch diameter has a smaller influence on the forces than the step in z axis, but has the same influence; with its growth forces are greater.

Both types of FEM analyses are in very good agreement with the experimental data.

In this experiment we could not take into account the material thickness while we obtain different mechanical characteristics. As future research we consider the realization of an experiment of type 3³ for more detailed assessment of the strains distribution and relative thinning and forces of straight groove parts and to elaborate mathematical models that would allow the determining the deformations and forces.

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