INFLUENCE OF TOOL PATH ON MAIN STRAINS, THICKNESS REDUCTION AND FORCES IN SINGLE POINT INCREMENTAL FORMING PROCESS

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Abstract: *The purpose of this study was to investigate the influence of tool path by optical methods on main strains distribution and relative thinning and forces using a dynamometer in single point incremental forming process. For this purpose the authors have chosen a dome part. In the tests were used three types of tool paths: first with constant vertical step, second with angular constant step and the third a loxodrome.*

Key words: *single point incremental forming, FEM modelling, simulation, strains, forces, measurement.*

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 (Fig. 1a) and two points incremental forming (TPIF which use besides the small punch a male (Fig. 1d) or female (Fig. 2c) die, a support post (Fig. 1e) or a second intender (Fig. 1b). 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. This sheet metal forming process has a high potential for small quantity production and for rapid prototyping applications.

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 incomprehensible 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].

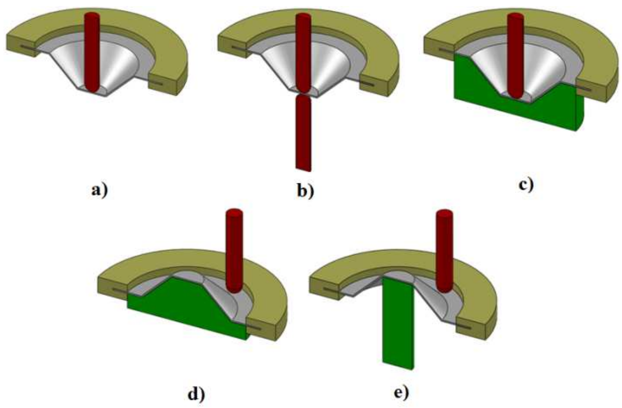

Fig. 1. Incremental forming types with a small intender.

There is also researches that used multi-step tool path to obtain parts with vertical walls having 900 [6] or to investigate hybrid processes [12], a combination of ISF with stretch forming.

This study aims to determine the influence of tool path on main strains and thickness reduction for dome parts.

2. EXPERIMENTAL TESTS

2.1. Parts manufacturing

Due the process complexity and to the inexistence of a specialized machine for this metal forming process, the authors conducted the experiments on a Haas MiniMill CNC milling machine. The experimental testing installation is composed of the CNC milling machine and the forming equipment. Forming equipment was installed on the CNC machine as can be seen in Fig. 2. It is composed of a bottom plate that has two carriers that support the die, a punch and a retaining ring. Dies have various shapes such as circular, square, triangular and other.

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Table 1

The mechanical characteristics of material

Thickness [mm]	***K* [Mpa]**	***n***	**ε_u [%]**	**R_{00}**	**R_{45}**	**R_{90}**
0.7	533	0.22	49.48	1.77	1.44	2.15

For the dome parts was used a circular die, with the inside circle having a diameter of 55.5 mm and 6 mm radius. For all components were used a punch with a diameter of 8 mm. To move the punch was used a feed rate of 240 mm / min with a punch rotary speed of 180 rpm. To reduce friction at the contact between the punch and the material, forming lubricant was used. The material chosen to produce single point incremental forming parts is a deep drawing DC04 steel, with thicknesses 0.7. The specimens used during testing are cut into squares of 120 mm side length.

The mechanical characteristics of the sheet were determined on a tensile test machine Roell RKM & Korthaus 100/20. The obtained data are presented in Table 1.

Path of the traveling tool is most crucial for the successful product by the incremental forming process. In Fig. 3 are presented various tool paths adopted to obtain a dome part. The traveling tool moves clockwise.

Three kinds of tool paths up to the goal shape are implemented as follows:

Tool path 1: starting position is at the center-bottom of the position circle, as can been seen in Fig. 3c. Traveling tool is intending vertically to the sheet plane with a constant z step and moves in the horizontal direction inducing plastic deformation locally around the contact area following a circle path with a certain radius, as can been seen in Fig. 3b. The vertical step is 1 mm.

Tool path 2: stating position and the punch travel are the same as in the first case, except the step. In this case punch executes an intend with an angular constant step (Fig. 3b). The angular step is 6°.

Tool path 3: the tool follows the path described by the loxodrome presented in the Fig. 3c. The punch executes a simultaneous movement in all three directions at the same time.

Fig. 2. Experimental equipement used for SPIF.

2.1. Strains measuring

To measure the deformation the samples were marked before deformation electrochemical. We used a network of points with diameter of 1 mm and a 2 mm distance between center points as can see in Fig. 2b. Mark was made on the part that does not come in contact with the punch (Fig. 4). To measure the strains optical system ARGUS was used, produced by the GOM company. Deformations were measured with a camera with 12 mm focal length lens.

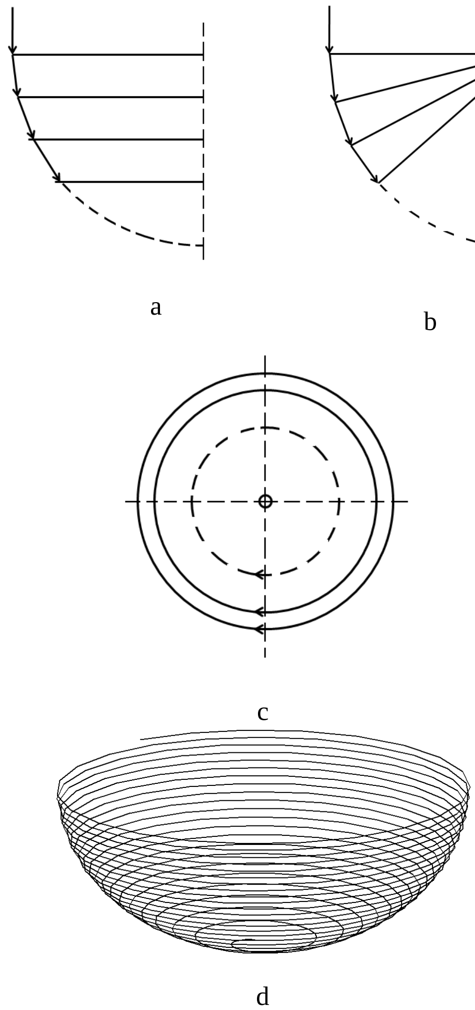

Fig. 3. Punch traiectories: *a* – constant vertical z step; *b* – constant angular step; *c* – circular motion in *xOy* plane; *d* – loxodrome.

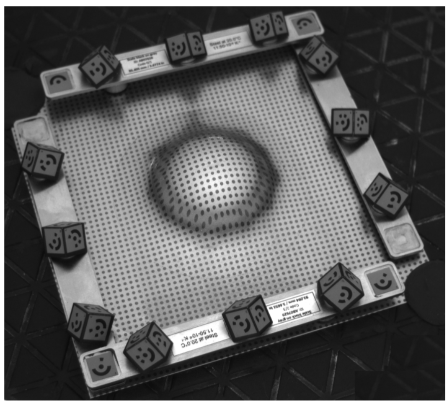

Fig. 4. Part with coded bars and markers for optic analysis.

The pieces were placed on a rotating table. On the pieces were 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 and a set of images captures by rotating the table with 15–20 degrees. Then the camera is positioned at an angle of 45 degrees from the part plane and again captures a set of images by rotating table with 15 to 20 degrees.

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

Figures 5, 6 and 7 present the main strains for the all trajectories.

Figures 8, 9 and 10 present the second strains for all parts. From the figures can been observed that for the first two tool paths secondary strains have maximum values in the area where the punch intend in vertical direction for each step. For the third case the distribution of secondary strains is more homogenous and has a maximum value in the area where the punch starts to intend into material. In this case, as in the case of the main strain, the most favorable tool path is the third tool path. For minor strains the worst case is case 1 with a vertical constant step.

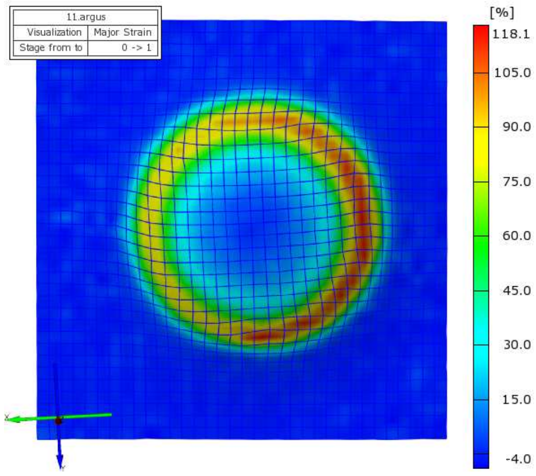

Fig. 5. Main strains for tool path 1.

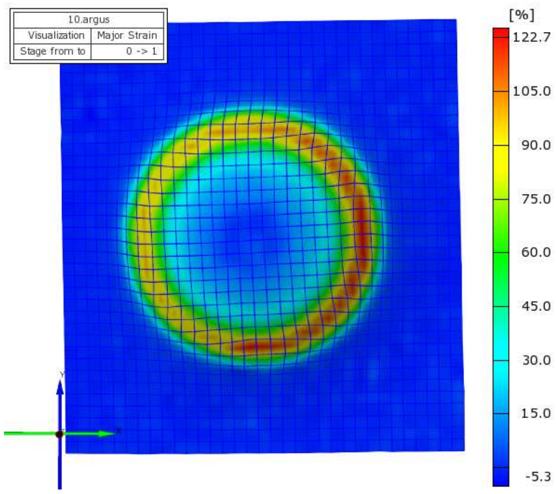

Fig. 6. Main strains for tool path 2.

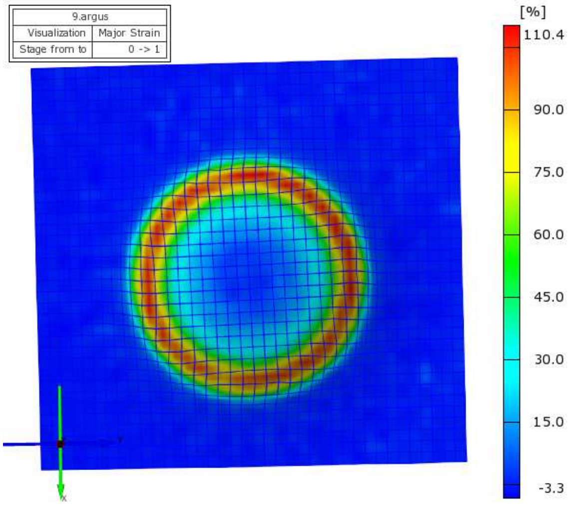

Fig. 7. Main strains for tool path 3.

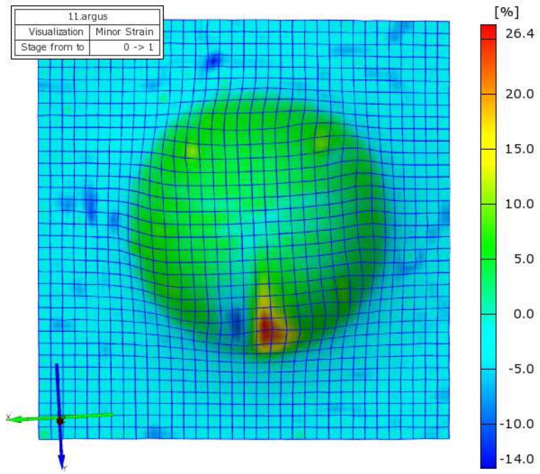

Fig. 8. Secondary strains for tool path 1.

Table 2

The experimental results for deformations

Tool path	ε_1 max [%]	ε_2 max [%]	*vM* [%]	*thk* [%]
1	118.1	26.36	186.3	63.3
2	122.7	18.5	176.4	61.44
3	110.4	11.26	144.9	55.32

Figures 11, 12, and 13 present the relative thinning for dome parts. From these figures we can been observed that relative thinning have a similar distribution as main strains.

As can been seen from the figures main strain varies in the *xOy* plane. The strains have maximum values in the area where the punch starts the circular movement in *xOy* plane. For the first and second tool paths the strain values decrease with the punch movement and for the third case the strains have a more homogenous distribution. In the Table 2 are presented the results for all three parts. The most favorable tool path in terms of main strain is the third tool path, the loxodrome. The worst case in terms of major strains is the case 2, a tool path with constant angle movement.

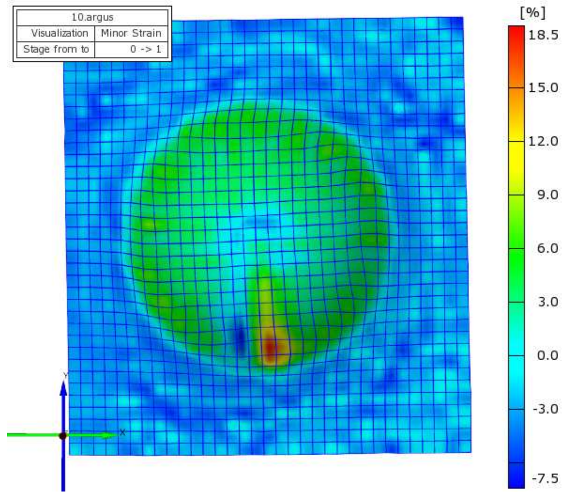

Fig. 9. Secondary strains for tool path 2.

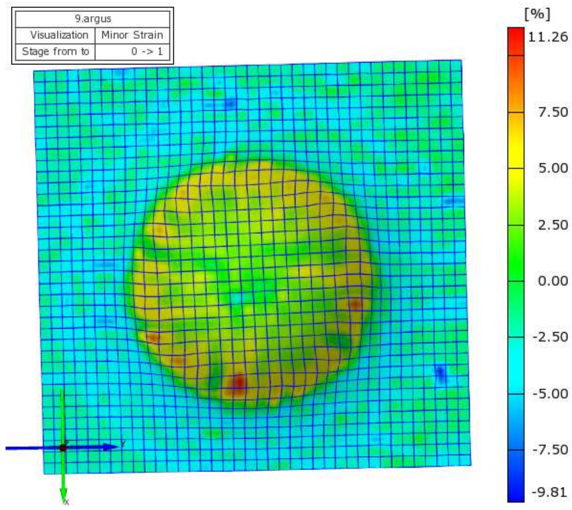

Fig. 10. Secondary strains for tool path 3.

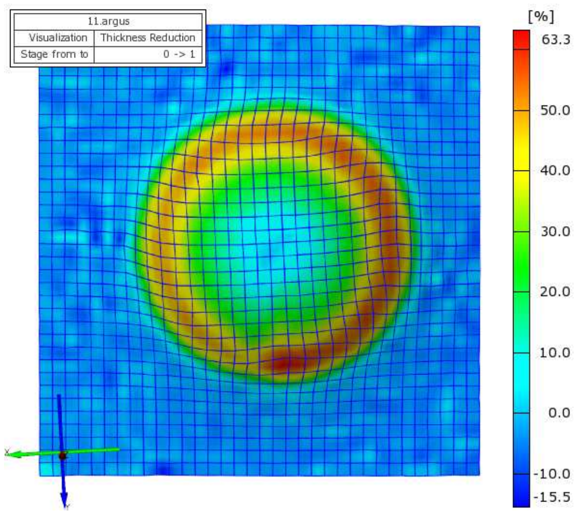

Fig. 11. Thickness reduction for tool path 1.

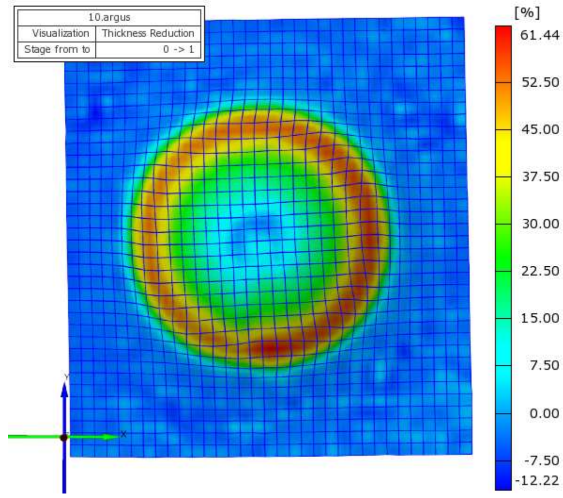

Fig. 12. Thickness reduction for tool path 2.

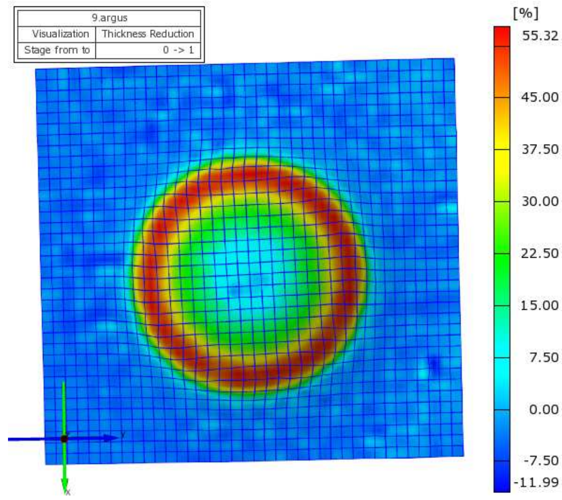

Fig. 13. Thickness reduction for tool path 3.

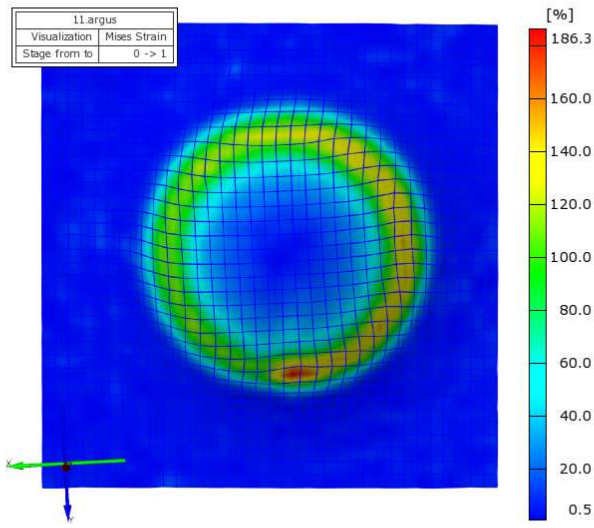

Fig. 14. Von Mises strains for tool path 1.

For the first and second cases relative thinning have maximum values in the area of punch intend into material and then this values decrease. For the third case relative thinning has a homogenous distribution and this case is the best case in term of relative thinning. The worst case is the case 1 with constant vertical step.

Figures 14, 15 and 16 present the von Misses strains for all parts types. For the first and second case these strains have the same distribution as the main strains and relative thinning, maximum values in the area where the punch starts to move in *xOy* plane. For the third case von Misses strains have a more homogenous distribution and

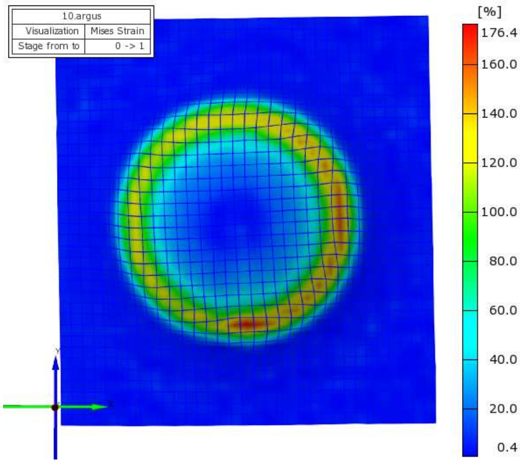

Fig. 15. Von Mises strains for tool path 2.

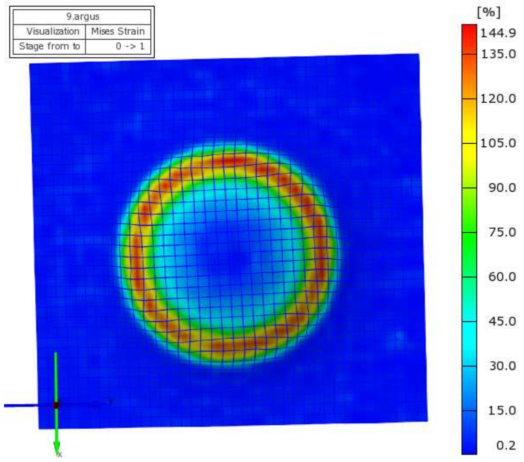

Fig. 16. Von Mises strains for tool path 3.

lower values than in the other two cases. The worst case for von Misses strains is the case 1 for constant vertical step.

2.3. Forces measuring

Forces of single point incremental forming process were determined using a dynamometer installed under the forming equipment.

From the dynamometer were taken stamps strain gauges signals, which were mounted in bridge on its rings and through an instrument made in the Mathlab program were converted tensions into strengths. Before that, dynamometer was calibrated to determine the dependent relationships between tension on strain gauges stamps and some calibrated weights.

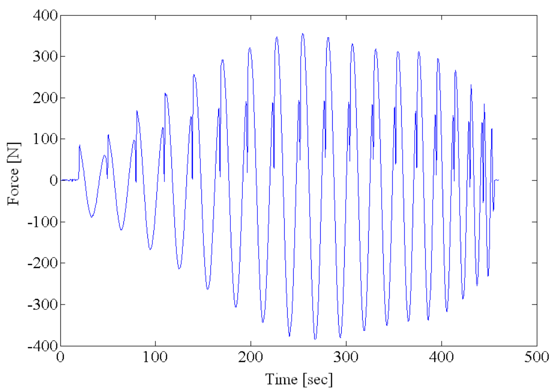

Fig. 17. F_x for tool path 1.

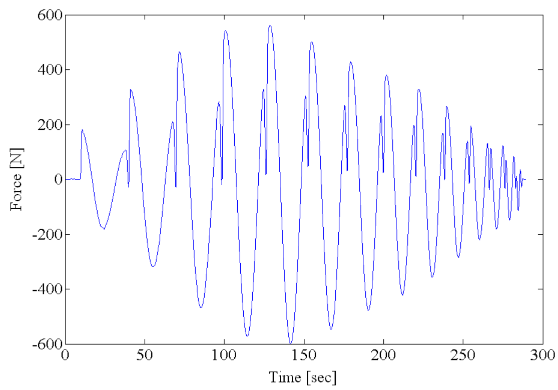

Fig. 18. F_x for tool path 2.

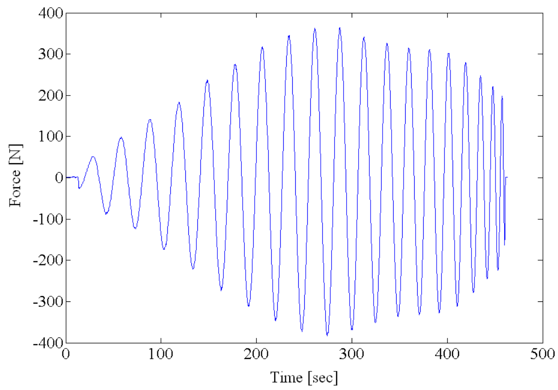

Fig. 19. F_x for tool path 3.

Table 3

The experimental results for forces

Tool path	F_{xmax} **[N]**	F_{zmax} **[N]**
1	355.6	871
2	562.5	1265
3	364.2	768

Acquisition frequency of forces in two directions is 100 samples / sec.

In Figs. 17, 18 and 19 the forces on x direction, a direction in sheet plane, are presented. As can been seen from the figures and Table 3 the most favorable tool path for forces in x direction is the first case, a constant vertical step. Forces in x direction for the first and second case have the same shape for each circular motion in xOy plane. At each punch penetration we have a peak force and at the end a sudden drop. In the third case the forces have a continuous sinusoidal shape.

In Figs. 20, 21 and 22 the forces for vertical direction are presented. As in the case for forces in x direction the first and second case have the same shape for each punch penetration with a circular motion in the sheet plane. The third case has a continuous shape without local peaks or sudden drop. The most favorable case is the case third, the loxodrome and the worst the second case, for constant angular tool path.

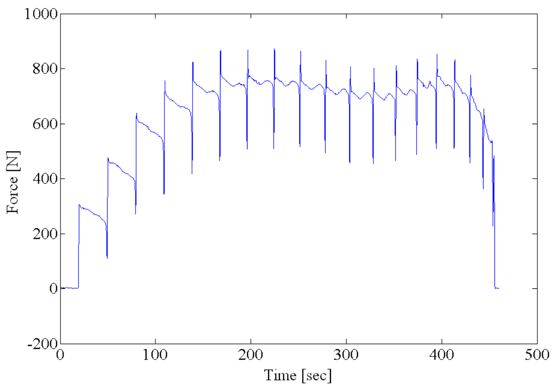

Fig. 20. F_z for tool path 1.

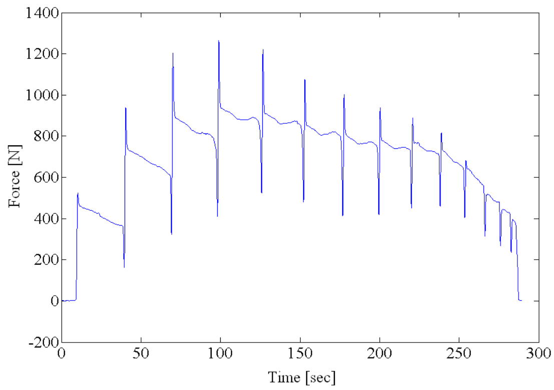

Fig. 21. F_z for tool path 2.

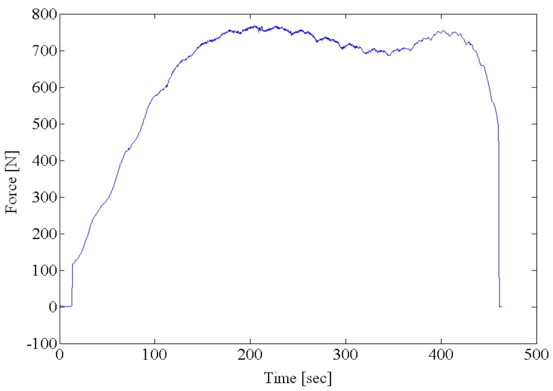

Fig. 22. F_z for tool path 3.

3. CONCLUSIONS

Deformation behavior of sheet metal in an incremental process for various tool paths is investigated using optical methods. For main strains, minor strains, von Misses strains and thickness reduction the most favorable tool path is the loxodrome. With this tool path the strains distribution is more homogenous and the values are lower than in the other two cases.

In the case of forces measurement we have the same results as in the case of strains measurement. The best results are for the third case, for tool path that follow a loxodrome. The forces shape is more homogenous without local peaks or sudden drop or forces.

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