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INCREMENTAL FORMING – AN ALTERNATIVE TO TRADITIONAL MANUFACTURING METHODS

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Abstract: *New manufacturing technologies are developed fast in order to keep up with the market demands, both in the field of metal cutting and metal forming. The Asymmetric single point incremental forming (ASPIF) is a manufacturing technology with a high degree of novelty, which allows the user to manufacture complex parts by metal forming, using only a punch and an active plate without the need of using dies. Even if there are a significant number of research results reported in the literature, which demonstrated the advantages of the ASPIF, the industry has not been very enthusiastic to adopt and implement it on large scale. There are still some drawbacks which prevent the implementation of ASPIF at industry level, such as low accuracy of the parts and sheet metal integrity. The paper presents some approaches of implementing this process using as technological equipment either CNC milling machines or serial industrial robots. Both simulation and experimental data are presented. The influence of the processing toolpaths upon the accuracy of the parts, upon the strains and the thickness reduction has been shown. The authors also proposed a set of computer assisted techniques which can be used in order to make the ASPIF process more efficient and industry-friendly.*

Key words: *CNC milling machine, industrial robot, incremental forming, CAD, CAM, CAE.*

1. INTRODUCTION

Asymmetric single point incremental forming (ASPIF) has been recognized as a solution with great potential in manufacturing small batches or single sheet metal parts [1 and 2]. A description of the ASPIF process principle is presented in Fig. 1. The blank (2) is fixed by the blank holder (3). In order to realize the shape of part, one of the active elements, usually the punch (1) has an axial feed movement on vertical direction, continuous or in steps s (incremental), while the other element, the active plate (4) carries out a plane horizontal movement.

However, in spite of its great potential, the industry is still reluctant to apply the ASPIF process on a large scale, due to two major drawbacks: low shape and dimensional accuracy of the parts and sheet metal integrity [3, 4, and 5].

A flowchart of the computer assisted techniques which may be involved in the ASPIF process is presented in Fig. 2. The following acronyms were used in Fig. 2: CAD – computer aided design, CAE – computer aided engineering, CAM – computer aided manufacturing.

While the CAD stages of the process (building the 3D model, exporting/importing the CAD neutral file) and the CAE stages (FEA analysis and simulation) may be carried out using well known CAD/CAE tools, the situation with the CAM stages (generating the processing trajectories and the NC code and processing the part) is somehow different.

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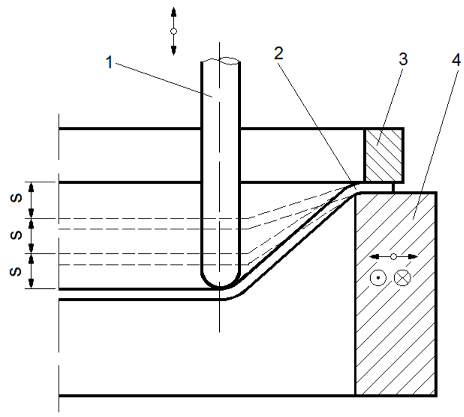

Fig. 1. The ASPIF process.

The CAM software packages are intended to be used mostly for cutting processes, turning and milling. Using them for the ASPIF process may be quite difficult.

Normally, a CAM program automatically generates the toolpaths by means of the final shape of the 3D model of the part, taking into consideration the cutting tools and the cutting process. Because the ASPIF process and tools (punches) are not implemented in the any existing CAM program, the above mentioned automated toolpath generation cannot be performed. Consequently, this leads to the need of using only simple toolpaths (seen as the trajectories of the punch) for ASPIF.

The most used toolpaths reported in the literature are simple contour curves, obtained by cross-sectioning the 3D model of the part with horizontal planes, equally spaced on *Z* axis. Figure 3 shows a 3D model of a simple sheetmetal part (Fig. 3a) and the contour curves toolpaths (Fig. 3b).

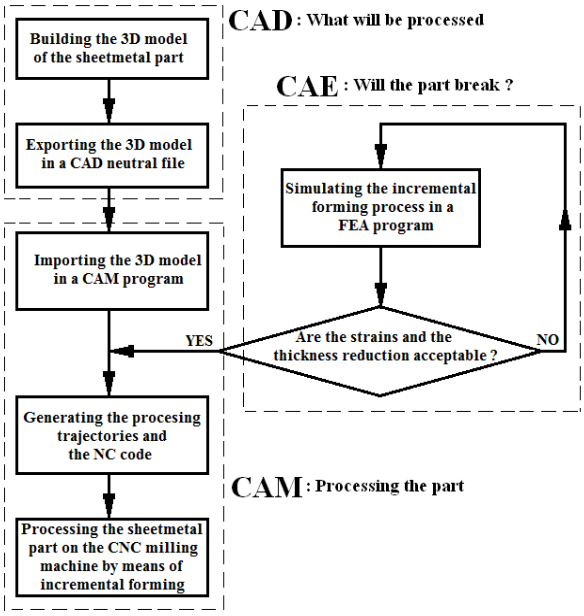

Fig. 2. Flowchart of computer assisted techniques for the ASPIF process.

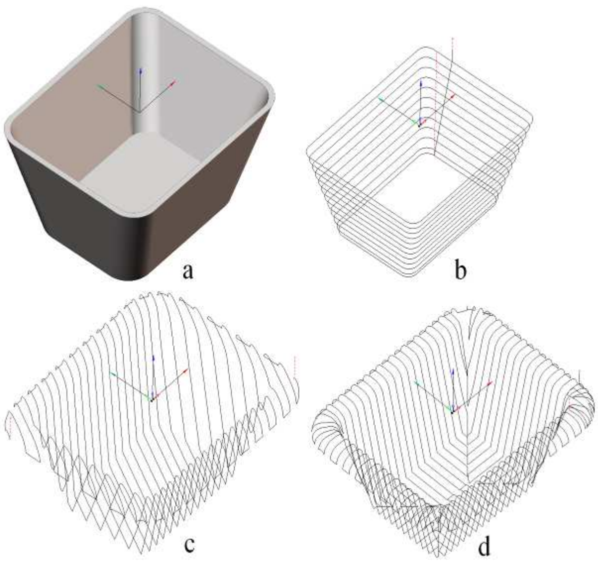

Fig. 3. 3D model (a), contours curves (b) and complex processing toolpaths (c, d).

More complex toolpaths such as drive curves oriented at a specific angle to X axes (Fig. 3c) or two-orientation toolpaths (Fig. 3d) can be used, but the generation of such toolpaths could be very difficult.

2. USING CNC MILLING MACHINES AS TECHNOLOGICAL EQUIPMENT

The experimental researches have targeted the realising of parts with complex shapes, in conditions of high dimensional precision.

Therefore, there was chosen as technological equipment for the experimental researches the numerical controlled milling centre Haas MiniMill, presented in Fig. 4. The numerical controlled milling centre use simplified dies, on which there can be obtained a large number of part typo-dimensions, as opposed to the classical process, where a die is used for realizing a single type of part.

Fig. 4. The CNC milling centre Haas MiniMill.

Therefore, it was opted for using a forming die with a set of exchangeable die plates, which, when used in the incremental deep drawing process for bimetallic sheets, allows a detailed research of their behavior during forming, by means of the realising of several part typo-dimensions.

2.1. Manufacturing a hemispherical part – a first set of toolpaths

Three kinds of tool paths up to the goal shape are implemented as presented [7] in Fig. 5.

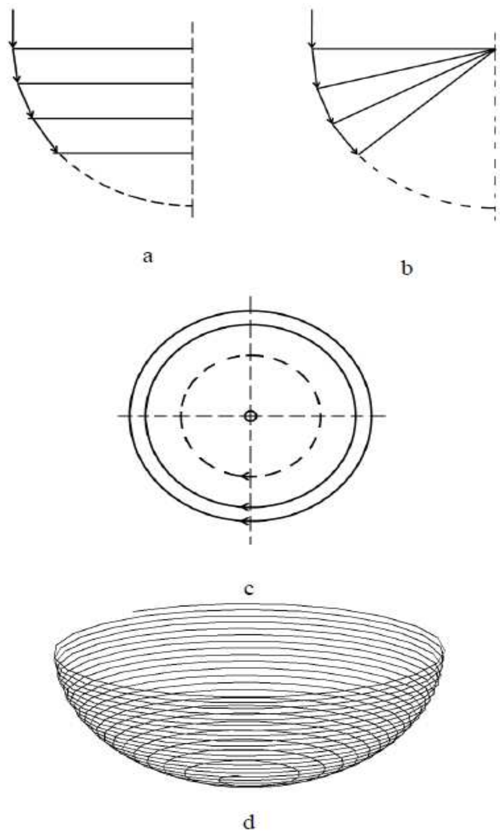

Fig. 5. Punch trajectories: *a* – constant vertical z step; *b* – constant angular step; *c* – circular motion in xOy plane; *d* – loxodrome.

Tool path 1: starting position is at the center-bottom of the position circle, as can been seen in Fig. 5c.

The tool trajectory 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. 5b.

The vertical step (increment) used within this approach was 1 mm.

Tool path 2: stating position and the punch trajectory are the same as in the first case, except the step. In this case the punch executes an intend with an angular constant step (Fig. 5b). The angular step was considered 6˚.

Tool path 3: the tool follows the path described by the loxodrome presented in the Fig. 5c. The punch executes a simultaneous movement in all three directions at the same time.

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 Matlab 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.

The most favorable case is the case third, the loxodrome and the worst the second case, for constant angular tool path.

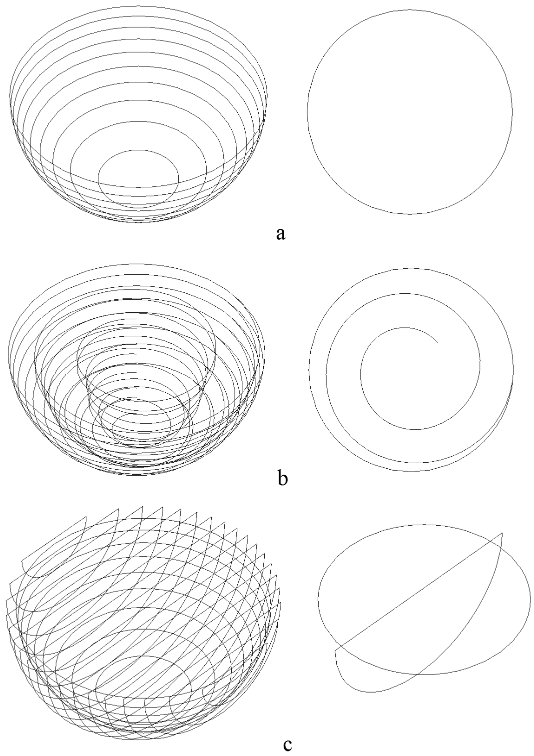

Fig. 6. The use of different toolpaths for processing a hemispherical part.

2.2. Manufacturing a hemispherical part – a second set of toolpaths

A hemispherical part was processed using a double layer blank: an outer layer of steel, with better mechanical properties and an inner layer of aluminum alloy.

In a first approach, circular trajectories in the horizontal *XY* plane, spaced 1 millimeter between each other on the *Z* axis were used to obtain the shape of the part, Fig. 6a.

The second approach was to generate the hemispherical shape starting with an Archimedes spiral, completed with a circle in the *XY* plane and also translate these trajectories along the *Z* axes, reducing both the spiral step and the circle radius, Fig. 6b.

A third approach involved processing of the parts in two stages: a roughing stage, where horizontal circular trajectories were used, each circle having the diameter smaller by 2 millimeters as the part's diameter and a finishing stage, when circular trajectories in a plane perpendicular on *XY*, *XZ* plane, were used to obtain the final shape and dimensions of the parts, Fig. 6c.

Both the circular curves and the Archimede's spiral were built in the CAM program, a software package specifically designed for milling.

The NC code was generated automatically by the CAM program and a ball-nose milling tool was considered, in order to emulate the punch.

A processed part is presented in Fig. 7, with an outer layer of DC04 steel and an inner layer of AA6016 aluminum alloy.

In order to test the effectiveness of the proposed method, an experimental analysis of the strains was carried

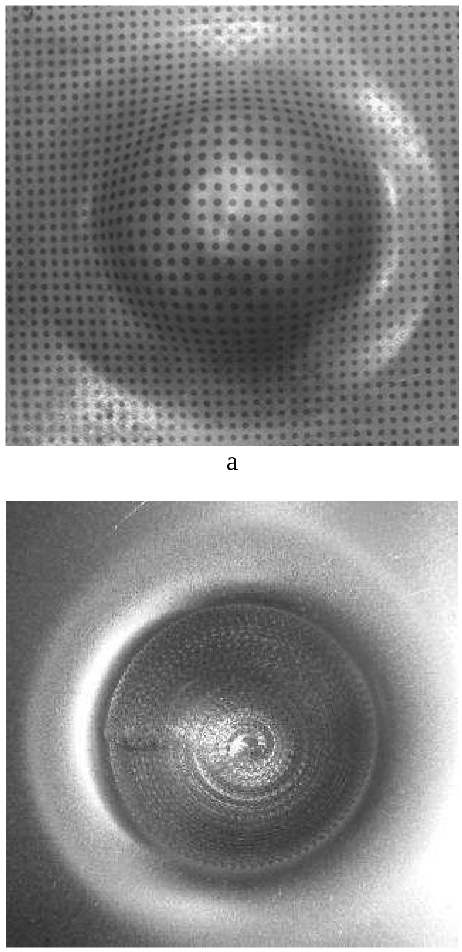

Fig. 7. Processed part: *a* –hemispherical part (outer layer DC04 steel); *b* – hemispherical part (inner layer AA6016 aluminum).

Table 1

Maximum values of the strains

Tool-path	Maximum major strain ε_1 [%]	Maximum minor strain ε_2 [%]	Maximum equivalent Von Mises strain ε_{VM} [%]	Maximum relative thickness reduction s_{max} [%]
Circles	91.70	17.35	128.70	54.25
Spiral	66.17	14.92	92.00	45.76
Two-stages	102.00	51.80	187.1	64.91

out using ARAMIS optical measurement system, which allows the user to determine the main, secondary and equivalent strains on the sheet metal parts, after a metal forming operation. The optical measurement system also include software for data evaluation and processing, with image registration and post processing control, automatic scanning of a series of images, 2D and 3D views

The major (ε_1) and minor (ε_2) strains, the Von Misses strains (ε_{VM}) and the thickness reductions (s_{max}) were determined. The maximum measured values are synthesized in Table 1.

Considering the parts generated by simple trajectories as reference, the relative thickness reduction, major and minor strains and Von Misses strains were found to be significantly smaller for the parts processed using Archimedes spiral trajectory.

All of the above mentioned inputs were higher for the parts processed in two stages, roughing and finishing.

The distribution of the strains (major, minor and von Misses) was more uniform for Archimedes spiral trajectories and for two stages processing, compared with the reference trajectories, with no local maximum points, which eliminates the possibility of cracks.

Consequently, using complex toolpaths, such as Archimedes spiral trajectories, could lead to significantly better results than the use of simple circular contour curves.

Building an Archimedes spiral using a CAM program is quite a simple an automated process, and based upon the constructed curves, the software packages generates the processing toolpaths and the NC code automatically.

3. USING INDUSTRIAL ROBOTS AS TECHNOLOGICAL EQUIPMENT

The system used for simulating and obtaining the toolpath for the incremental forming experiments consists of a six degrees of freedom anthropomorphic robot, KUKA KR 6, Fig. 8, a custom blank holder, a custom tool holding unit and the forming tool.

The KUKA KR6 robot has great flexibility and is suitable for both point-to-point and continuous-path controlled tasks [14].

The tridimensional models of the robotic system components that were designed in CATIA V5 are presented in Fig. 9.

Using a specific function from DELMIA software package, an accurate tridimensional model for the

Fig. 8. Custom stand and KUKA KR6 robot.

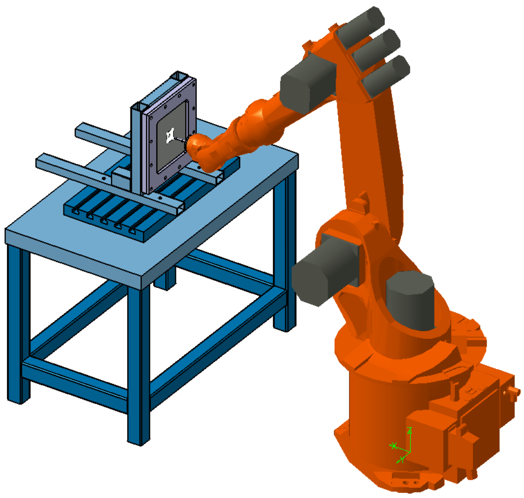

Fig. 9. Tridimensional model of the robotic system used for the simulation.

KUKA KR 6 robot was imported in the simulation environment.

DELMIA is one of the most powerful virtual prototyping applications in manufacturing. DELMIA has various applications like 3D model design, process planning, resources planning, discrete and continuous event simulation, 3D visualization, layout planning and virtual reality, all in the same platform.

In order to demonstrate the capabilities of the method described above, a truncated pyramid sheet metal part was manufactured using a custom made stand and with the help of a KUKA KR6 anthropomorphic robot.

The sheet metal part can be manufactured directly from the CAD model without the need of a die plate. The dimensions of the desired sheet metal part are presented in Fig. 10.

The material used for the sheet metal part was a St 14 mark of steel with a thinness of 0.4 millimeters. The forming tool used in this experiment was a hemispherical head punch with a diameter of 6 millimeters [8].

The first step in the manufacturing of the test part is to design the part itself in a CAD environment, a task which was performed using CATIA software package. A tridimensional model of the truncated pyramid is presented in Fig. 11.

The second step is to design the tool path needed for the experiment in CATIA. The tool path required for the manufacturing of the truncated pyramid is presented in Fig. 12. Following the necessary steps, according to the stages of the simulation methodology, a program code was generated by means of the “Create program” function from DELMIA software.

After transferring the necessary files to the KUKA KR 6 robot controller, the experiment can be executed. The finished sheet metal part is presented in Fig. 13. The duration of the forming process was approximately 5 minutes.

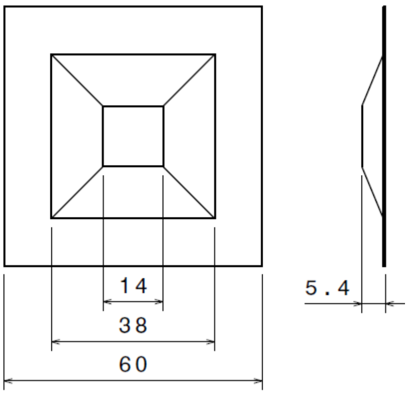

Fig. 10. Dimensions of the test part.

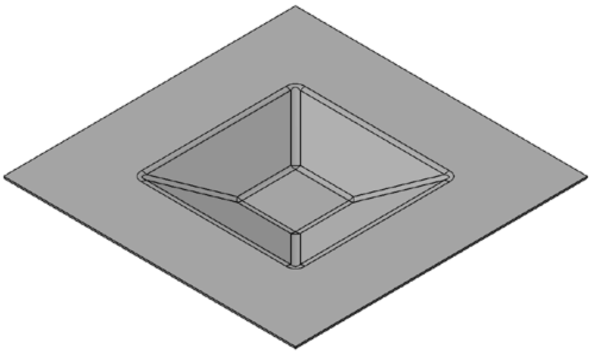

Fig. 11. CAD model of the test part.

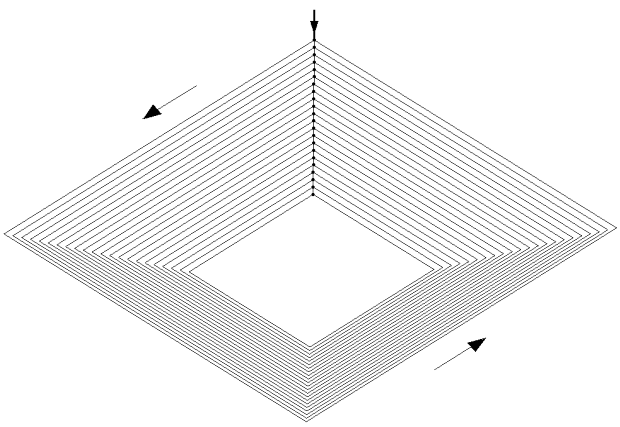

Fig. 12. Tool path for the test part.

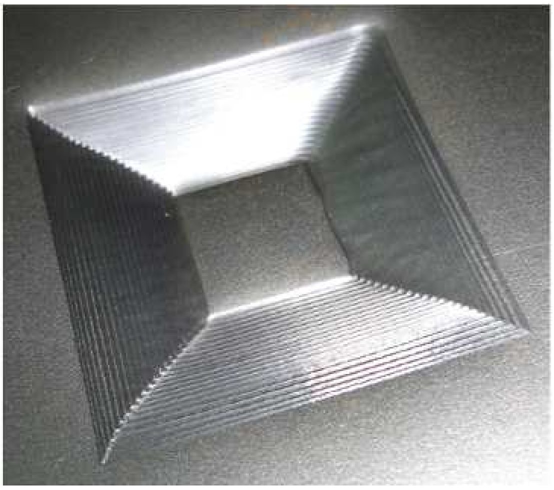

Fig. 13. Finished sheet metal part.

4. CONCLUSIONS

New manufacturing technologies are developed fast in order to keep up with the market demands, both in the field of metal cutting and metal forming.

Incremental forming of sheet metal parts can be a reasonable alternative to traditional methods especially for producing prototypes and small batches.

These low volume production orders require an increased level of flexibility in order to minimize the costs. Basically, the technological equipment has to be a motion control system, able to control the controlled movements of the punch and the active plate. Also, this equipment has to be able to withstand the technological forces within the process, which have values bigger than the ones involved in cutting processes, for example. Consequently, this leads to the use of CNC milling machines and industrial robots which meet the above-mentioned requirements. There were reported some custom-design machines, dedicated for this manufacturing process, but their use was restricted to scientific research. Moreover, using custom-design machines could increase the cost of producing the parts, to an unacceptable level.

The paper presented some experimental results of processing parts by means of ASPIF process, using either CNC machine tools or serial industrial robots.

In the first part of the paper, the process of manufacturing a hemispherical part using a single layer blank was described.

A set of toolpaths (seen as the trajectories of the relative movements of the punch), with constant vertical step, with constant angular step, with circular motion in xOy plane and loxodrome were tested and compared. The results had shown that the loxodrome is the best approach, by the point of view of technological forces involved in the ASPIF process.

The second sets of experiments involved the manufacturing of a hemispherical part using a double layer blank. A new set of toolpaths, of greater complexity was used, one of these involving the processing the part in two stages: a roughing and a finishing stage. The results have been analyzed by the point of view of strains distribution and thickness reductions.

The experiments have demonstrated that the use of combined toolpaths, consisting of circular contour curves and Archimedes spirals lead to better results than other approaches.

A knowledge base regarding the technological parameters of the process, the behavior of the two layers blank, the influence of the toolpaths and the accuracy of the parts were also created.

The third set of experiments has demonstrated the possibility of using serial industrial robots for processing parts by ASPIF.

The low rigidity of the industrial robot structure and the difficulty of programming continuous toolpaths (instead of point-to-point trajectories) have been overcome by designing and building a special processing layout for supporting the part, designing and building a working unit, which carries the punch and by using specific programming software.

A KUKA KR 6 robot was used as technological equipment and DELMIA software package was used for generating the control program. In this initial stage, only simple toolpaths were used and no comparisons were made.

Further researches will try to investigate the influence of the toolpaths upon the technological forces, strains distribution, thickness reduction and accuracy of the parts, when processing parts with more complex shapes. Also, materials with greater strength, such as titanium alloys will be processed, at room temperature on CNC milling machine and using a custom design heating system, attached to the KUKA KR 6 robot. The custom design heating system is now in testing stages in the laboratories of the authors' institution.

Finally, one of the most important objectives of the further researches will be to find analytical relations to calculate the technological forces within the ASPIF process. Now, even the estimation of these forces is a cumbersome process, and the estimated forces are usually quite different from their real values, a situation which can damage expensive technological equipments as CNC machines and/or industrial robots.

REFERENCES

[1] J. Jeswiet, F. Micari, G. Hirt, et al., *Asymmetric Single Point Incremental Forming of Sheet Metal*, Annals of CIRP, 54(1), 2005, pp. 623–650.

[2] V. Oleksik, A. Pascu, C. Deac, R. Fleaca, M. Roman, *Numerical Simulation of the Incremental Forming Process for Knee Implants*, Proc. COMPLAS X, X International Conference on Computational Plasticity, Fundamental and Applications, eds. E. Oriate and D.R.J. Owen, Barcelona, 2009.

[3] V. Oleksik, O. Bologa, R. Breaz, G. Racz, A. Găvruș, *Numerical simulations and experimental researches regarding the precision of the incremental forming process*, The 12th Conference on Metal Forming, Krakow – Poland, September 21–24, 2008, published on Steel Research International, No. 79 (2008), Special Edition, Volume 1,Verlag Stahleisen Gmbh, pp. 591–594.

[4] V. Oleksik, A. Pascu, D. Mara, O. Bologa, G., Racz, R. Breaz, *Influence of geometric parameters on strain and thickness reduction in incremental forming process*, The 13th Conference on Metal Forming, Toyohashi, Japan, September 19–22, 2010, published on Steel Research International, Vol. 81 (2010), Special Edition, nr. 9, Verlag Stahleisen Gmbh, pp. 930–933.

[5] M. Rauch, et al., *Tool path programming optimization for incremental sheet forming applications*, Computer-Aided Design, 41, 2009, pp. 877–885.

[6] F. Micari, G. Ambrogio, L. Filice, *Shape and dimensional accuracy in single point incremental forming: State of the art and future trends*, Journal of Materials Processing Technology, 191 (1–3), 2007, pp. 390–395.

[7] A. Blaga, O. Bologa, V. Oleksik, R. Breaz, *Influence of Tool Path on Main Strains, Thickness Reduction and Forces in Single Point Incremental Forming Process*, Proceedings in Manufacturing Systems, Vol. 6, Iss. 4, 2011, pp. 191–196

[8] I. Chera, O. Bologa, G. Racz, R. Breaz, *Robot-Forming – An Incremental Forming Process using an Industrial Robot by means of DELMIA software package*, Applied Mechanics and Materials Vol. 371 (2013), Trans Tech Publications, Switzerland, 2013, pp. 416–421.

[9] L. Filice, L. Fantini, F. Micari, *Analysis of Material Formability in Incremental Forming*, Annals of the CIRP, 51(1), pp. 199-202, 2002.

[10] M. Bambach, B. Taleb Araghi, G. Hirt, *Strategies to improve the accuracy in asymmetric single point incremental forming*, Production Engineering Research Development, 3, 2009, pp. 145–156.

[11] M.R. Morovvati, B. Mollaei-Dariani, M.H. Asadian-Ardakani, *A theoretical, numerical and experimental investigation of plastic wrinkling of circular two-layer sheet metal in the deep drawing*, Journal of Materials Processing Technology, 210, 2010, pp. 738–1747.

[12] R. Breaz, O. Bologa, M. Tera, G. Racz, *Researches Regarding the Use of Complex Trajectories and Two Stages Processing in Single Point Incremental Forming of Two Layers Sheet*, The 14th Conference on Metal Forming, Krakow - Poland, September 16–19, 2012, published on Steel Research International, Special Edition, Verlag Stahleisen Gmbh, 2012, pp. 427–430.

[13] E. Ceretti, C. Giardini, A. Attanasio, *Experimental and simulative results in sheet incremental forming on CNC machines*, Journal of Materials Processing Technology, 152 (2), 2004, pp. 176–184.

[14] KUKA KR6 Robot Manual.