Incremental forming – CAE/CAM approaches and results

G S Racz, V S Oleksik and R E Breaz
“Lucian Blaga” University of Sibiu, Engineering Faculty, Department of Industrial Machines and Equipment, 4 Emil Cioran, 550025 Sibiu, Romania
E-mail: radu.breaz@ulbsibiu.ro

Abstract. Metal forming is one of the most important group of manufacturing technologies used in many branches of machine-building industry. The Metal Forming Research Centre (MFRC) at Lucian Blaga University of Sibiu acts as both research and technology transfer facility, aiming to bridge the gap between theoretical research and industrial implementation in this field. The paper presents the results obtained during the last years by the research team of MFRC in the study of incremental forminga promising process of dieless forming, with a high flexibility and great potential for industrial implementation.

1. Introduction
Incremental forming is a flexible manufacturing process which allow the user to manufacture small batches of sheet metal parts in a flexible way, with reduced costs associated with tools (dies) and auxiliary devices. Single point incremental forming (SPIF), a variant of the process is based upon a combination of three basic movements (figure 1), which made it suitable for implementation on CNC (computer numerically controlled) machine-tools.

![Figure 1. Schematic diagram of SPIF, [1].](image)

Movement I represent the vertical displacement of the punch, performed along the Z axis using incremental vertical steps, while movements II and III are usually performed in a continuous way by the sheet metal workpiece in the horizontal (XY) plane.

2. Theoretic and experimental researches regarding the plasticity of the processed parts
One of the first attempts to study the strains ad thickness reduction at the end of SPIF process was presented in [2]. The punch diameter and vertical incremental step were considered as influence parameters. Two types of materials, with different thicknesses were used for the experimental program. An optical measurement system Argus from GOM was used as measuring device, which
underwent a calibration process. The experimental setup for the calibration process is presented in figure 2.

![Figure 2. Experimental setup for calibration, [2].](image)

Figure 3 presents the evolution of $\varepsilon_1$ main strain while figure 4 depicts the variation for the relative thickness reduction for the points situated in a YOZ plane-oriented section for the same situation.

![Figure 3. Evolution of $\varepsilon_1$ main strain, [2].](image)  
![Figure 4. Relative thickness reduction evolution, [2].](image)

The experiments have revealed that punch diameter is the most important influence factor. Thus, the strains and thickness reduction are increasing with the decrease of the punch diameter. The vertical incremental step also influences these values, in the same manner: the strains and thickness reduction are increasing with the reduction of the incremental step, which also leads to an increase in the number of passes required to process the part.

Another work oriented to the study of strains and thickness reduction was presented in [3]. Same processing and measuring strategies were used, but this time the experimental researches were oriented to find the most favourable toolpath. A cone-frustum shape with 12mm maximum height and 55° side angle was used as test shape.

The spatial spiral toolpath was found as the best approach, because the mains strains and relative thickness reduction distribution was found to be more homogenus in this case. Also, the relative thickness reduction was found to be smaller. Measured values for main strains $\varepsilon_1$ and $\varepsilon_2$ and for relative thickness reduction are presented in figures 5-7.
Figure 5. Variation of main strain $\varepsilon_1$ for the spiral toolpath, [3].

Figure 6. Variation of main secondary strain $\varepsilon_2$ for the spiral toolpath, [3].

Figure 7. Variation relative thickness reduction for the spiral toolpath, [3].

2.1. Using industrial robots for incremental forming

Another work by the research team aiming mostly the study of relative thickness reduction was presented in [4]. A KUKA KR 6-2 serial industrial robot was used as technological equipment. The most important advantage of using an industrial robot instead of a CNC milling machine (aside of its superior kinematics) was the fact that the strains and relative thickness reduction could be measured online, during the process, not only after finishing it. The experimental setup is presented in figure 8 and the variation of the relative thickness reduction at different moments during the SPIF process is presented in figure 9. The optical measurement system which allowed the measurement of main and secondary strains and the relative thickness reduction during the process was an Aramis from GOM.

Figure 8. Experimental setup for SPIF with KUKA KR 6-2 robot, [4].
2.2. Numerical simulation by means of FEM

A comparison between incremental forming and conventional stretch forming, by means of FEM simulation was presented in [5]. Three variants of simple toolpaths presented in figure 10 were used for the SPIF process.

![Toolpaths](image)

**Figure 10.** Three variants of toolpaths considered during the numerical simulations, [5].

The numerical analysis targeted the relative thickness reduction, the time variation of Von Misses equivalent stress, the evolution of the forming forces and the accuracy of the processed parts.
The simulated evolution of the relative thickness reduction for the parts processed by SPIF using each toolpath and for the part processed by conventional stretch is presented in Figure 11.

A comparative numerical-experimental study with regards of the best formulation for the Thin shell 163 element was presented in [6]. The LS-DYNA software package was used and four formulations for the Thins shell 163 element were used: formulation 2 (Belytscho-Tsay), formulation 25 and two relatively new formulations – formulation 16 (Belytscho-Tsay formulation with stresses on element thickness) and formulation 26 (fully integrated formulation with stresses on element thickness). Four separate analyses were unfolded, targeting the main strains and the forming forces. The simulated results were compared with the experimental ones (figure 12).

**Figure 11.** Variation of relative thickness reduction: (a) – incremental forming first toolpath; (b) – incremental forming second toolpath; (c) – incremental forming third toolpath; (d) conventional stretch, [5].
3. Influence of the toolpaths upon the accuracy of the parts – CAM approaches

A first approach of studying the influence of the processing toolpaths upon the accuracy of the parts was presented in [7], where a hemispherical part was used as test shape. Simple circular contours curves, complex composed toolpaths consisting of an Archimedes spiral, completed with a circle in each plane and two-stage forming trajectories were studied comparatively, figures 13-15.

Figure 12. Variation of the main strain $\varepsilon_1$ for: formulation 2 - Belytschko-Tsay (a); formulation 26 (b); formulation 16 Belytscho-Tsay with stresses on element thickness (c); formulation 26 fully integrated formulation with stresses on element thickness (d); experimental results measured with Argus (e), [6].

Figure 13. Circular trajectories, [7].

Figure 14. Complex composed trajectories: (a) spatial toolpaths; (b) Archimedes spiral, completed with a circle, [7].

Figure 15. Two-stages forming: (a) spatial toolpaths; (b) toolpaths in XZ plane, [7].
The complex composed trajectories were found as the best approach by the point of view of parts accuracy, figure 16.

![Figure 16. Dimensional accuracy of the parts: (a) 0° cross-section (b) 90° cross-section, [7].](image)

A complex part was used as test shape in [8] and six processing strategies using CAM software generated toolpaths were studied using AHP (Analytic Hierarchy Process) analysis which targeted many aspects (accuracy, formability, surface quality ease of generation and processing time). Figure 17 presents a comparison with regards of parts accuracy for the six machining strategies.

![Figure 17. Accuracy comparison between the six proposed strategies, [8].](image)

The AHP analysis revealed that the strategy presented in figure 18 using a roughing stage (using contour curves, stock of 2 mm left for finishing stage) and a finishing stage (using two passes: first pass with toolpaths parallel to X axis, second pass with toolpaths perpendicular to X axis) was the best approach.

![Figure 18. The best strategy revealed by AHP analysis, [8].](image)
4. Processing bio-compatible materials by means of incremental forming at room temperature
The incremental forming process is also a suitable approach for manufacturing prosthetic devices. In [9] the research team from MFRC presented a method of processing a cranioplasty plate from Ti6Al4V alloy, at room temperature. Figure 19 presents the 3D model of the cranioplasty plate, while figure 20 presents the processed part.

![Figure 19](image1.png)

Figure 19. 3D model of the cranioplasty plate: (a) upper side; (b) lower side, [9].

![Figure 20](image2.png)

Figure 20. Processed part: (a) upper side; (b) lower side, [9].

5. Artificial intelligence methods used for SPIF processing force estimation
An adaptive network-based fuzzy inference system was designed to calculate the vertical technological force, considered as an output [10, 11]. The considered inputs were the punch diameter, the processing feed and the incremental vertical step. The approach did not aim to develop an analytical expression for calculating the vertical force values, but to develop an adaptive network-based fuzzy inference system which allows the user to estimate in an empirical way the force for a given set of process parameters and their variation intervals. The system was built using Matlab software packages and its modules, Fuzzy Logic and Neural Network toolboxes. The structure of the fuzzy inference system is presented in figure 21.

![Figure 21](image3.png)

Figure 21. Structure of the fuzzy system, [11].

6. Conclusions
The researchers presented in this paper were oriented to provide results aimed to speed the industrial implementation of the incremental forming process. The MFRC has proven itself during its existence both by its research infrastructure and its human resources as a reliable partner for both research organizations and industrial companies. The main targeted industrial areas of application for incremental forming are considered automotive industry and aeronautics. Several research projects, with MFRC as partner are now in progress, among their main objectives being the industrial implementation of incremental forming.
7. References

[1] Breaz R, Tera M, Ciubotariu V A, Cohal V, Maier C and Plaiausu G 2018 Single point incremental forming - comparison between technological equipment by an overall processing time point of view Proceedings in Manufacturing Systems 13(3) 121-126

[2] Oleksik V, Pascu A, Mara D, Bologa O, Racz G and Breaz R 2010 Experimental research about the influence of geometric parameters on strain and thinning distribution of the incremental forming process, Steel Res. Int. 81(9) 930-933

[3] Blaga A and Oleksik V A 2013 Study on the Influence of the Forming Strategy on the Main Strains, Thickness Reduction and Forces in a Single Point Incremental Forming Process Adv. Mater. Sci. Eng. 2013(2)

[4] Oleksik V 2014 Influence of geometrical parameters, wall angle and part shape on thickness reduction of single point incremental forming The 11th International Conference on Technology of Plasticity, Nagoya, Japan Procedia Engineering 81 pp 2280-2285

[5] Oleksik V, Bologa O, Breaz R and Racz G 2008 Comparison between the numerical simulations of incremental sheet forming and conventional stretch forming process Int. J. Mater. Form. 1 Suppl. 1 1187-1190

[6] Oleksik V, Pascu A, Rosca L and Bondrea I 2013 Numerical-Experimental Comparison Study Regarding Single Point Incremental Forming Process Numiform American Institute of Physics 1532 pp 532-537

[7] Breaz R, Bologa O, Tera M and Racz G 2012 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 Steel Res. Int. Special Edition pp 427-430

[8] Tera M, Breaz RE, Racz SG and Girjob C 2019 Processing strategies for single point incremental forming-a CAM approach Int. J. Adv. Manuf. Technol. (online) 1-17

[9] Racz S G, Breaz R E, Tera M, Girjob C, Biris C, Chicea AL and Bologa O 2018 Incremental Forming of Titanium Ti6Al4V Alloy for Cranioplasty Plates-Decision-Making Process and Technological Approaches Metals 8(8) p 626

[10] Tera M, Breaz RE, Bologa O and Racz S G 2015 Developing a Knowledge Base about the Technological Forces within the Asymmetric Incremental Forming Process Key Engineering Materials 651 pp 1115-1121

[11] Racz S G, Breaz R E, Bologa O, Tera Mand Oleksik V S 2019 Using an adaptive neuro-fuzzy inference system (ANFIS) to calculate the vertical force in single point incremental forming, Int. J. Comput. Commun. Control. 14(1) 63-77

Acknowledgments
This research was partially funded by the Romanian Ministry of Research and Innovation CCCDI-UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0446/nr. 82PCCDI/2018, within PNCDI III, project title: “Smart Manufacturing Technologies for Advanced Production of Parts from Automotive and Aeronautics Industries”.