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Contributions regarding the incremental forming of complex parts using robotic systems

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Contents

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Abstract

Manufacturing processes by plastic deformation have a wide applicability in: the automotive industry, aerospace industry, consumer goods industry, electronics and electrical industry and also food industry.

In the last decades, the concept of intelligent manufacturing has been developed. One of the most important aspects of this concept is related to flexibility in manufacturing. The market generated the need for flexibility in terms of diversity in demand from the population all over the world. Conventional methods of plastic deformation such as deep drawing and punching offer countless advantages for mass production, but for the production of prototypes and pre-series components, the manufacturing of dies is not justified because of high costs.

For this reason, as a result of the research in cold plastic deformation field, new processes were developed for the manufacturing of the sheet metal parts. Incremental forming comes as a solution to the aforementioned problem, because it does not require the use of dies in the classical variant. This method uses deformation tools with simple geometries and can be implemented using various machinery, such as: specially built incremental forming machines, CNC milling machines and industrial robots.

In order to manufacture a sheet metal part using incremental forming method, usually the forming tool (a punch) carries out an axial movement continuously or in steps in the direction perpendicular to the surface of the sheet metal blank, and the mounting system for the sheet metal blank, performs a plane-horizontal movement. The main characteristic of this process is that during the forming process, only a small part of the part surface is in contact with the forming tool. This process has a high level of flexibility because we can obtain a wide variety of hollow shaped parts, using the same machinery and using the same forming tool with the same support plate for the blank.

Continuing the study of incremental forming process initiated by researchers from the Centre for Research on Metal Forming (CSCDP) at the "Lucian Blaga" University of Sibiu was taken into account when the topic for this Ph.D. thesis was chosen.

The Ph.D. thesis is structured in seven chapters which present aspects of theoretical and experimental research regarding single point incremental forming process of sheet metal parts.

The first chapter presents the motivation of the research carried out in the context of the tackled topic, as well as the evolution and structure of the Ph.D. thesis.

The second chapter, entitled “State of the Art in the Field of Incremental Sheet Metal Forming Processes” starts with an overview of the process and the classification of different kind of incremental forming processes. Next, the technological equipment and the tools used in incremental forming processes were presented.

The next subchapter was dedicated to incremental forming done with an additional local heating. The sources for heating the sheet metal blanks are: electrical resistors, laser sources, and heating by electrical induction.

In the subchapter dedicated to alternative incremental forming processes, a series of equipment were presented which are designed to improve on certain aspects considered drawbacks in the standard procedure for incremental forming. The alternative methods are: incremental forming by hammering and water jet incremental forming.

Also as part of this chapter the areas of application for the parts obtained by the incremental forming are presented. At the end of chapter two, the research directions of this Ph.D. thesis were outlined.

Chapter three, entitled "Theoretical Research Regarding the Incremental Sheet Metal Forming Processes" includes analytical calculations related to the discussed procedure, with regard to the state of deformation and the maximum deformation angle.

By expressing the maximum forming angle in relation to the geometrical dimensions of the incremental forming system led to a relationship that cannot be solved analytically. Based on the results obtained by researchers from experimental research, the expression of the maximum forming angle could be expressed in relation to the fracture forming limit (FFL) of the blanks material. Knowing the slope of the fracture forming limit curve, the numerical value of the maximum forming angle could be determined.

To complete the mathematical description through analytical procedures based on the plasticity theory, the modeling of the forming processes by means of numerical methods has steadily been gaining importance in the last decades. The finite element method stands out and has applicability on a large scale in the field of engineering calculations. This method can achieve calculated results very close to those obtained in experimental research.

Chapter four, entitled "Numerical Simulation of the Single Point Incremental Sheet Metal Forming Process Using the Finite Element Method" presents the results obtained by applying the finite element method to the virtual model of the incremental forming process.

In the first subchapter, the mathematical apparatus used by most analysis programs for the non-linear domain is presented. To solve the nonlinear analysis, a parameterized model of the incremental forming system has been designed using ANSYS program. Solving the finite element analysis was done using LS-DYNA program.

The first type of finite element analysis sought to determine the influence of the geometrical parameters of the incremental forming system on the major and minor strains and also to the relative thinning of the material of the blank.

The geometrical parameters that were considered are the punch diameter D_p, the incremental step p_z and the forming angle ψ. In order to determine the influence of these parameters two types of analyzes have been performed. The first type of analysis observed the influence of the punch diameter D_p and the incremental step p_z over the strains and thinning variation for truncated pyramid shaped parts with a height of 23 mm. The second type of analysis observed the influence of the forming angle ψ for truncated pyramid shaped parts with a height of 16 mm.

The third type of finite element analysis sought to determine the influence of different types of trajectories over the strains and thinning variation of the blank. For this type of analysis, four distinct trajectories have been designed, resulting (at the end of the analyses) four parts: truncated triangular pyramid, truncated square pyramid, truncated octagonal pyramid and truncated dodecagonal pyramid. The geometric shape for the basis of each part was inscribed in a circle with a diameter of 75 mm, to see in what way, adding multiple sides to the geometry of the basic influences the values of the strains and the thinning variation of the blanks material.

In addition to presenting the results that were obtained at the end of the analysis, there were also results which emphasize the evolution in time of the characteristic values during the single point incremental forming process simulation. The characteristic values that have been studied in this type of analysis are: the major strains, the minor strains, the relative thinning of the material and the nodal displacement of the material along the OZ axis.

For this type of finite element analysis, a punch with the diameter of 10 mm and an incremental step of 0.25 mm were used. The material thickness for the blank was defined as 0.4 mm. In this type of analysis, four types of trajectory paths are used: truncated triangular pyramid, truncated square pyramid, truncated octagonal pyramid and truncated dodecagonal pyramid. The evolution of the characteristic values, extracted from two sets of reference points located on the surface, has been studied. The first set of reference points is positioned on the edge of the part, in the area where the values for the minor strains display the greatest variation. The second set of reference points is positioned on the inclined wall of the part along the trajectory path of the punch, in the area where the values for the major strains display a significant variation.

The subchapter entitled "Determination of the values and the variation of the forces during the incremental forming process" presents the graphs of the variation of the forces (along the three axes OX, OY, OZ and resultant force) during the incremental forming analyzes mentioned above. The graphs for the forces were extracted using ANSYS program.

One of the main research directions of this Ph.D. thesis was the measurement of the strains respectively of the relative thinning of the material for the parts during the actual incremental forming process. In specialized literature, this method involves measuring the strains "on-line". The method uses ARAMIS optical measurement system to capture real-time images of the parts, and then analyze them. Thus, the characteristic values for the incremental forming process can be determined. Using the "on-line" measurement method requires the face of the blank that does not comes in contact with the forming tool to be exposed to the optical cameras of ARAMIS measurement system. The optimum distance recommended by the manufacturer for the measurement between the sheet metal blanks and ARAMIS cameras is about one meter. Taking this aspect into account, arose the second research direction: designing an experimental stand that is able to incremental form sheet metal parts and allows the "on-line" measurement of the characteristic values.

From these two main research directions arose the third line of research, namely finding a technological equipment that is be able perform the incremental forming but not to obstruct the optical field of the cameras that perform the "on-line" measurement of the strains. After consulting the literature in the field concerned, it was noticed an increase in the use of industrial robots as work equipment for experimental research of incremental forming of sheet metal parts. Thus, we opted to use an industrial robot with six degrees of freedom, KUKA KR6.

Chapter five, entitled "The design of the trajectories of the forming tool attached to the industrial robot used for Single Point Incremental Sheet Metal Forming" presents the steps required in order to obtain the program code for controlling the industrial robot used for the single point incremental forming of sheet metal parts. The trajectories paths used in finite element analysis and for experimental research have been designed using CATIA V5 program.

The research described in the subchapter "Simulation of path trajectories of the forming tool" were aimed mainly on simulating and validating the path trajectories of the robot that were used either in finite element analysis or for experimental research of single point incremental forming process. The simulation and validation of the path trajectories was done using DELMIA program. DELMIA software can generate and export the program code needed for commanding the industrial robot used for the single point incremental forming.

The sixth chapter, entitled "Experimental Research Regarding the Single Point Incremental Sheet Metal Forming Process“ in the first part presents results related to experimental research aimed to determine the actual properties of the blank material used for incremental forming. The data obtained was used to define the material properties for the finite element simulations of the single point incremental forming process. The experimental study of the single point incremental forming process is presented in the second part of the chapter.

The subchapter entitled "Experimental equipment used for research" presents various facilities used for the experimental research such as the experimental stand used for the study of the incremental forming process, ARAMIS optical measurement system and INSTRON 5587 uni-axial tensile test machine.

The research described in the subchapter "The determination of the material properties of the sheet blanks through axial tensile testing" are aimed at obtaining real data regarding the sheet metal blanks material required by LS-DYNA program when simulating the incremental forming process. The input for the material properties is a curve defined by pairs of points that represent real deformations and real tensions. The uniaxial tensile test method was chosen to test the deformability of the blanks.

This method consists of fixing a test specimen at both ends inside of the INSTRON 5587 uni-axial tensile test machine, deforming it at a constant speed, until the specimen breaks. The tensile strength is being read by means of a force transducer and the strains with an extensometer. The determination of the anisotropy coefficients was performed using ARAMIS optical measurement system which was used as an extensometer.

The section entitled "The influence of geometrical parameters over the characteristic values of the single point incremental forming process" presents research results aimed at establishing the influence of geometrical dimensions such as the punch diameter D_p, the incremental step size p_z and the forming angle ψ over the characteristic values: major stains, minor strains and the relative thinning of the blanks material.

The first type of experiment emphasized the influence of the punch diameter D_p and the incremental step p_z over the characteristic values. For these tests three values were used to define the diameter of the punch, and three values to define the incremental step, resulting in a total of nine test experiments. The shape chosen for the incremental formed parts was a truncated square shaped pyramid.

The second type of experiment emphasized the influence of the forming angle over the characteristic values. For these experimental tests, four distinct trajectories paths were designed, resulting in four truncated square shaped pyramid parts with the inclination angle of the walls at 45°, 55°, 65° and 75°.

The purpose of experimental tests presented in the subchapter "Determining the influence of different types of trajectory paths over the characteristic values" is to determine the influence of different types of trajectories for the forming tool have over the major stains, minor strains and the relative thinning of the blanks material. For this type of experiment, six distinct trajectory paths were designed, resulting from experimental tests, six parts with different geometries: truncated triangular pyramid, truncated square pyramid, truncated pentagonal pyramid, truncated hexagonal pyramid, truncated octagonal pyramid and truncated dodecagonal pyramid. The geometric shape for the basis of each part was inscribed in a circle with a diameter of 75 mm, to see in what way, adding multiple sides to the geometry of the basis of the parts influences the values of the strains and the thinning variation of the blanks material.

In addition to the results that were obtained at the end of the analysis, ARAMIS optical measurement system provides to the user, the characteristic values at different stages of the single point incremental forming process.

The subchapter "Determining and analyzing the variation in time for the characteristic values of the incremental forming process" presents series of images emphasizing the time evolution of the major strains, the minor strains and relative thinning of the blanks material.

Such results differentiate ARAMIS optical measurement system from other measurement systems like ARGUS. ARGUS optical measurement system uses the same two high-resolution cameras, but can only measure the shape of the parts at the end of the deformation process. In addition, ARAMIS optical measurement system provides to the user graphics and numerical results showing the time variation of the characteristic values of incremental forming process in any point on the surface of the part.

In order to study the evolution in time of the strains and the relative thinning of the material during the single point incremental forming process, two sets of reference points located on the surface of the part were defined. From these reference points, the characteristic values were extracted at different stages of the process using ARAMIS program. With the help of the first set of reference points, positioned on the side edge of the part, the variation of the minor strains was emphasized. With the help of the second set of reference points, positioned on the inclined wall of the part, along the trajectory path of the punch, the variation of the major strains and the thinning variation of the material were emphasized.

The subchapter entitled "Determining the influence of the geometrical parameters on the shape accuracy of the incremental formed parts" emphasizes the results aimed to determine the influence of the geometrical parameters (punch diameter D_p, incremental step p_z, forming angle ψ) on the shape accuracy of the parts obtained by the single point incremental forming. ARAMIS optical measurement system provides to the user the three-dimensional surface for the measured parts. The surface of the formed parts may be exported as a .stl file, which may in turn be imported into the majority of CAD programs. Using CATIA V5, the surfaces of the formed parts were compared with the CAD (theoretical) models of the parts. The experimental tests mentioned above sought to determine the level difference Δ_h of the top of the parts to the theoretical profile. The maximum values for the level difference were recorded in the middle of the basis of the truncated pyramid.

The last chapter, entitled "Conclusions - The main contribution of the paper" summarizes the conclusions and the achievements of the Ph. D. thesis out of which are worth mentioning:

Conclusions:

- incremental forming is suitable for sheet metal forming, in particular for the development of prototypes or for pre-series components at a reasonable cost;
- this forming method presents a high degree of flexibility because it uses tools with simple geometries and can be performed using various equipment such as: specially built incremental forming machines, CNC milling machines and industrial robots;
- non-linear finite element analysis method can be successfully implemented to simulate the single point incremental forming process;
- the major strains, the minor strains and the relative thinning of the blanks material have an uneven distribution on the surface of incremental formed parts. In the case of

the major strains, the maximum values were mostly concentrated along the path trajectory of the punch on the inclined facets of the parts;

- the values of the resulting force from the forming process increase when the diameter of the punch increases; the values of the resulting force from the forming process increase also when the forming angle increases;
- on the other hand, the values of the resulting force from the forming process decrease, when adding multiple sides to the geometry of the basis of the parts;
- from experimental research on incremental forming process it was observed that if the punch diameter increases, the values for the strains and the relative thinning of the material decrease. On the other hand, when the values for the incremental step increase, the values for the strains and the relative thinning of the material also increase;
- as in the case of the finite element analyzes, there was a pronounced localization of the maximum values for the major strains along the path trajectory of the forming tool on the inclined facets of the parts;
- if the values of the forming angle were increased, the values for the strains and the relative thinning of the material also increased;
- using ARAMIS optical measurement system, it was possible to obtain results that emphasize the time variation for the characteristic values during the whole incremental forming process;
- the values for the major strains and the relative thinning of the material even out on the inclined walls with the increasing of the number of sides defining the geometry of the basis of the incremental formed parts;
- the shape precision of the incremental formed parts decreases when the values defining the punch diameter increase;
- the shape precision of the incremental formed parts increases when the values defining the incremental step increase;

Main contributions of the Ph.D. Thesis:

- developed a bibliographic study of the main scientific results related to tackled topic;
- developed a mathematical relationship defining the bi-axial strains acting on the material of the part during the incremental forming process;
- developed a mathematical relationship defining the maximum forming angle according to specific geometrical parameters of the incremental forming system;

- developed a mathematical relationship defining the maximum forming angle according to the slope of the fracture forming limit curve for the material of the blanks used in incremental forming process;
- developed a parameterized virtual model that allows the simulation of the single point incremental forming process. The virtual model of the blanks, the forming tool and the support elements were designed using ANSYS software;
- using the parameterized virtual model designed using ANSYS software, a series of explicit dynamic analysis for single point incremental forming process were carried out using LS-DYNA simulation software;
- obtained the distribution graphics for the major strains, minor strains and the relative thinning of the material for the incremental formed parts;
- assessed the influence of the punch diameter, the incremental step and the forming angle over the major strains, minor strains and the relative thinning of the material for the incremental formed parts;
- assessed the influence of multiple number of sides defining the geometry of the basis of the incremental formed parts over the characteristic values of the process;
- assessed the temporal variation of the characteristic values of the process on the surface of the incremental formed parts;
- assessed the temporal variation of the resistant forces of the single point incremental forming process;
- designed the tridimensional model of the experimental stand used for experimental research of the single point incremental forming process using CATIA V5 software;
- designed the path trajectories for the forming tool attached as an end effector to the industrial robot used for incremental forming process in CATIA V5 software;
- simulated the path trajectories for the forming tool attached as an end effector to the industrial robot used for incremental forming process in DELMIA software;
- generated the program code used for controlling the industrial robot used for incremental forming process in DELMIA software;
- conducted a series of uniaxial tensile strength tests in order to determine the actual characteristics of the blanks material used in incremental sheet metal forming;
- determined the actual stress-strain curve for the DC 04 steel grade with a thickness of 0.4 mm that was used for the incremental forming experimental tests;

- designed and manufactured an experimental stand that allows both single point incremental forming tests using an industrial robot and allows the "on-line" measurement of the strains respectively of the relative thinning of the material;
- successfully implemented the "on-line" measurement of the strains method using ARAMIS optical measurement system;
- conducted experimental tests in order to determine the distribution pattern of the strains and relative thinning of the material using different technological parameters and different trajectory paths. It was also established, how these parameters affect the maximum recorded values for the characteristic values;
- conducted experimental tests in order to determine the maximum forming angle for single point incremental formed parts;
- conducted experimental tests in order to determine the values and the distribution pattern of the strains and relative thinning of the material using different forming angles;
- conducted experimental tests in order to determine the influence of multiple number of sides defining the geometry of the basis of the incremental formed parts over the characteristic values of the process;
- conducted experimental tests in order to assess the temporal variation of the strains and relative thinning of the material;
- presented graphics emphasizing the variation of the characteristic values in relation to the cross-section of the incremental formed parts;
- compared the tridimensional model of the incremental formed parts with the CAD (theoretical) models using CATIA V5;
- assessed the shape precision for the incremental formed parts;
- determined the influence of the geometrical parameters over the shape precision for the incremental formed parts.