ABSTRACT

In recent years, there has been a worldwide desire for the increase of the flexibility of metal forming processes. This would be possible by increasing the flexibility of the forming tools. It is something intended both for the bulk forming processes and for the sheet metal forming processes. Among the newly emerged sheet metal forming processes, the single point incremental forming process is a modern metal forming method with enormous potential in terms of the degree of customization of produced parts.

In the single part or small scale production of sheet metal parts, the particularly high specific costs of dies and presses reflect negatively on the development of these technologies. Therefore, since there is an obvious trend towards individualizing the products, it is necessary to increase in future the flexibility in this area as well.

Due to the simplicity of the kinematics of the incremental forming process, the die can be mounted on various machines (numerical controlled milling machines, coordinate drilling machines, anthropomorphic robots etc.) or on a press having a coordinate movable table. The final form of the part is not obtained by copying the contour of one of the tools as in deep-drawing, but by a sequence of repeated pressings on the part made by tools with simple geometry. The pressing is incrementally repeated over the entire surface of the blank, on the desired path, thus obtaining the part’s surface as the envelope of the punch’s successive positions. In order to achieve the desired shape, the punch has an axial feed movement, perpendicular to the sheet metal direction, continuous or in steps, while the active plate has a movement in plane. The process has a high flexibility because, with the same punch and the same die but with different incremental movement trajectories, there can be obtained a plurality of hollow shapes.

Over time, the application fields of incremental forming have extended beyond the initial ideas of creating ribs on steel parts that had been previously deep drawn and now include fields such as medical implants, product rapid prototyping, architecture, automotive industry, forming equipment, aerospace and transportation industry and so on.

The structure of the habilitation thesis was designed to cover the essential elements of such a thesis, as follows: it contains the main scientific contributions of its author since being awarded the title of Doctor of Engineering Sciences, a chapter

covering career development and subsequent development proposals, the abstracts in Romanian and English and the references. The main scientific contributions are structured as follows: the state of the art in this field covering the period 2005 - 2016, the study of the variation of the forces and the determination of the influence of the main factors in the process, the analysis of the principal strains variation and of the thickness reduction, the study of the geometric precision, of the springback and of the roughness in the incremental forming process, the numerical simulation using the finite element method, the identification of the main applications of the incremental forming process (especially in the medical field) and, not least, finding a method based on inverse analysis to help identify the material coefficients that will be introduced in the numerical simulation programs.

The habilitation thesis begins with an introductory chapter outlining the main advantages and disadvantages of the incremental forming process but also its application areas.

The chapter dealing with the main scientific contributions of the author begins with a subchapter which tackles the research that took place in the field of the habilitation thesis beginning with 2005 (the year of the doctoral thesis defense) up to the present. In the beginning, there is presented the state of the art in terms of the force calculation in the incremental forming process and the existing mathematical models that approximate the calculation of forces. The chapter also includes a research aimed at validating these theoretical models through experimental research. Another line of research of the subchapter dealing with the state of the art refers to increasing the accuracy of the parts obtained through incremental forming. There are discussed also the main machines used in incremental forming (numerical controlled milling machines, industrial robots) and their influence on the obtained parts' precision. It is concluded that the milling machines are stiffer than the industrial robots and therefore the parts manufactured on milling machines are more accurate. Also there are presented here a number of online and offline strategies to improve the parts' accuracy. The chapter details the method which uses multivariate adaptive regression curves to predict the surface formed by incremental forming. It also presents techniques for the topological optimization of the punch's trajectory. Another subchapter presents the numerical and experimental researches that have focused on the thickness distribution (or thickness reduction) for the parts obtained through this process. A special attention is paid to the numerical simulation techniques using the finite element method. The tests are grouped according to the type of the used element: bi-dimensional or solid type. There are also presented the employed material models, algorithms and simulation methods as well as the optimization techniques used for the simulation. There are presented both studies that were conducted with commercial software (Abaqus, Ls-Dyna) and with software codes specially designed for simulating the sheet metal forming processes by different research institutions. Regarding the algorithms and the simulation methods, both the explicit and the implicit integration schemes are presented. Particular attention is paid to materializing the contact between the punch and the blank. Concerning the optimization techniques for simulating the incremental forming process, the subchapter presents the meshing and the adaptive re-meshing strategies. The advantages and the disadvantages of each strategy are emphasized, especially in terms of time spent for the analysis. At the end of this subchapter there is a brief study on the applications of the incremental forming process, especially those in the medical area, an area that has developed a lot over the last decade. The final subchapter tackles the possible directions for future research.

The second subchapter of the chapter dealing with the author's main scientific contributions covers the personal research in determining the forces variation in the incremental forming process. A first line of research aims at determining the maximum values of the forces on two directions (one vertical and one horizontal) and determining the influence of the punch diameter, of the blank’s initial thickness and of the part’s maximum height. The shape of the element obtained by incremental forming was of rib type, and therefore the parts were made with a single step on the vertical direction. For carrying out the experiments there was used a universal milling machine and the measurement of the forces on two directions was carried out by means of an elastic element. The electric signal acquisition has been achieved by means of a virtual instrument created using the TestPoint software. The blanks consisted of separated square blanks made of DC03 cold working steel. The conclusion reached was the following: both the vertical and the horizontal forces increase as the initial thickness of the blank increases; the height of the formed part also influences both the vertical force and the horizontal force on the direction of their growth as it increases; and the punch diameter influences the vertical force on the direction in which it increases as the diameter of the punch increases and the force on the horizontal direction slightly decreases when the diameter is increased. Further on, the experimental researches devoted to determining the forces in the incremental forming process have been diversified, following different trajectories. Different parts were made, including cone frustums, pyramid frustums, domes and so on. The machine used was a three axes milling machine. Thus, in order to make a dome-shaped part, two punches of different diameters were used, also employing two values of the vertical step. The conclusion was reached that both the increase of the punch diameter and the increase of the value of the vertical step led to the increase of the maximum values of the forces both vertically and horizontally.

Another line of research in the same subchapter aims to study the influence of the forming strategy (by changing the punch trajectory) on the forces in obtaining conical frustum type parts. It was notices that the most favorable trajectory is the spiral trajectory, where the variation of the vertical component of the force is smooth, without local maximum or minimum values and in addition to that, there is obtained a decrease of the maximum value by 23% compared to the other types of strategies.

The next subchapter deals with the studies conducted to determine the main strains and the thickness reduction in the incremental forming process. The subchapter is divided into two lines of research: the evaluation of the main strains and the thickness reduction at the end of the forming process and their evaluation throughout the forming process. The initial researches referred to the evaluation of the major strain and of the minor strain at the end of the process. A first research studied the influence of the geometrical parameters, more precisely of the punch diameter, and of the vertical step on the major strain and on the minor strain and on the thickness reduction. The measurements were performed on parts made of two different materials, with different thicknesses. The obtained parts were of pyramidal frustum type. The system used to measure the strains was an Argus optical system. Three different forming strategies (trajectories) were chosen. The conclusions that were reached were the following: the values of the main strains and the thickness reduction increase as the punch diameter decreases; the step on the vertical direction influences the maximum values of the main strains and the thickness reduction in the direction of their increase, as the value of the step decreases; and the value of the punch step on horizontal direction influences very little the maximum values of the strains and the thickness reduction. Another study in determining the main strains and the thickness reduction also focused on their determination at the end of the manufacturing process of conical frustum type parts performed with several different trajectories. Following the analysis of the main strains and the thickness reduction of the conical frustum type parts it was concluded that the optimal forming strategy is the one where the punch follows a spiral trajectory. The following research direction sought to determine the main strains and especially the thickness reduction throughout the forming process. The parts made were pyramidal frustums. In order to make the parts a Kuka robot was used and for measuring them there was used the Aramis optical system. Using the robot allowed to position the die vertically and automatically gave the opportunity to evaluate the main strains and the thickness reduction throughout the processing. It is assumed in incremental forming that the variation of the part's sidewall thickness abides by the sine law. The problem desired to be solved was the evaluation of the accuracy of the sine law in the incremental forming process. The research findings were the following: the sine law is obeyed only in terms of the maximum values of the thickness reduction in the incremental forming process, the maximum value of the thickness reduction is not reached at the outset but only after reaching a "critical value" of the part's height and both the distribution of the thickness reduction and its maximum values depend to some extent on the punch diameter and the value of the vertical step.

Another subchapter refers to the numerical simulation using the finite element method of the incremental forming process. The simulations were performed in order to make comparative studies of the main strains, the force variation and the spring back. The first study was a comparative one based on the finite element method between the single point incremental forming process and one of the conventional methods of forming sheet metal: stretch forming. Regarding the incremental forming process, three tests were conducted, each with a different forming strategy. Another line of research is aimed at the theoretical and experimental study of the single point incremental forming process in terms of the accuracy of the obtained parts. The study analyzes the level difference obtained at the bottom of the part, the spring back, but also the influencing factors: the punch diameter and its depth of penetration. Another numerical experimental comparative study intended to highlight the best formulations for the finite element of type Thin Shell 163 in simulating the single point incremental forming process. The major strain, the minor strain, the variation of the forces in the process and the spring back were analyzed and compared with the experimental results for four different formulations. Particular attention was paid to the spring back because the accuracy of the parts obtained by incremental forming mostly depends on it. It was noticed that the maximum value of the spring back is recorded close to the spot where the punch exits the material, somewhere in the side wall of the part.

A special subchapter deals with the applications of the incremental forming process in the medical field. A first research suggested the creation of implants for condylar surfaces in the knee. Numerical simulations using the finite element method were performed for this purpose. Other researches covered the evaluation of the surface quality of the implants for articular surfaces, a radial head and the phalanx base, obtained through incremental forming. The following influencing factors were considered: the quality of the punch surface, the friction coefficient and the punch diameter.

The final section of the chapter dealing with the major scientific contributions discusses a method based on inverse analysis for determining the mechanical properties of materials. The inverse analysis is basically the geometric modeling by the finite element method of the physical model which will be used for conducting the research and simulating the actual forming process. Parallel to this, the physical model is strained under conditions identical to those applied to the meshed geometric model, measuring certain response parameters. By decreasing the differences between the experimentally determined measurements and those obtained by simulation, we get the characteristic material values. The researches contained in this subchapter were based on the Erichsen test and on the Hecker test for determining the formability of the metallic or non-metallic materials. The material data obtained from the inverse analysis were validated by using them in the numerical simulation of the incremental forming process.

The last chapter of the habilitation thesis presents the author's teaching and research activity, the scientific contribution and the professional prestige as well as his career development proposals.