UNIVERSITATEA LUCIAN BLAGA DIN SIBIU

Interdisciplinary doctoral school

PhD field: Industrial Engineering

PhD THESIS - ABSTRACT

Studies and research on improving the dimensional and shape accuracy of parts processed by incremental forming

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SIBIU 2023

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KEYWORDS: INCREMENTAL FORMING, small thicknes sheet metal blanks, finite element method, ABAQUS EXPLICIT, numerical simulations, specific strains, material thinning, shear angle, material springback, accuracy deviations, KUKA KR 210-2, ARAMIS, Atos Core 200

ABSTRACT

Today's trends in the car manufacturing industry and not only, aim to reduce costs and production time as much as possible. The classic approach to the appearance of a new car concept involves the modification of some components of its body, the engineers trying to optimize a mold, and after the parts were made, various defects were highlighted, this whole process being repeated from the beginning, repeatedly.

The modern approach, based on the incremental forming process, allows engineers to produce prototypes at a much lower cost, since this process does not require a mold, but only two retaining rings for the sheet metal and a punch to deform it. This process has been given a lot of attention in recent years in the bibliographic literature, with the aim of optimizing it, as well as increasing the dimensional and shape accuracy of the deformed parts. [MAQ, 18].

During the incremental forming process, the punch follows a path preset by the user, gradually deforming the sheet blank fixed with the help of retaining rings. For the implementation of this process, it is suitable the use of machines with numerical control, due to the advanced possibilities of controlling their movement and rigidity, or industrial robots due to the superior kinematics, given by the greater number of degrees of freedom, as well as the higher workspace, which leads to greater flexibility regarding the shapes of the parts that can be made with them [TER, 19]. Toolpath design can be done with the help of CAM software used in machining processes, with specific adaptations to the incremental forming process or, as some researchers have proposed, using new software packages to generate the toolpaths [NAS, 18].

The incremental forming process has several important advantages, such as: low production costs, high flexibility, higher material deformability than conventional cold plastic forming processes such as deep drawing, and is advantageous for prototyping [MIC , 07, FIL, 13]. However, this process also presents some main drawbacks that prevent its industrial application and implementation in large series production [BRE, 19]. One of these disadvantages, perhaps even the most important, is given by the low accuracy of the parts processed by this process, regardless of the version of its implementation (with punch/active

plate total or partial/with counter punch/etc.). The researches undertaken within this work sought to find some theoretical and practical methods for reducing the effects of this drawbacks, and implicitly increasing the precision of the parts processed by this process.

After studying the bibliographic literature in the field of incremental forming, I noticed the following aspects:

- During the last years, different variants of the incremental forming process have been studied, from different tools used to different support elements for sheet metal blanks;
- The authors of the works studied the deformations and stresses that appear in the material through numerous theoretical and experimental methods;
- Numerous technological combinations of input parameters in the technological process were presented;
- Among the advantages of the process are the high flexibility given by the absence of an active plate, the possibility of processing parts with complex shapes, the possibility of processing metallic materials that have a high degree of deformability, etc.;
- The process is used in industrial applications where small series and unique parts are produced;
- The biggest disadvantage of the process is represented by the dimensional and shape accuracy of the parts processed by this process, which is relatively low, compared to that of the parts processed by other processes;
- Another disadvantage is represented by the relatively long processing time of a part;
- The most common defects of metal parts processed by incremental forming were identified, such as: the material springback, the deviation due to the "cushion" effect and the deviation due to the connection radius at the base of the parts;
- Numerous authors have proposed different algorithms for correcting toolpaths in order to increase the precision of parts;
- Several methods have been identified to measure and evaluate the dimensional and shape accuracy of the parts processed by incremental forming;
- Several methods have been presented to improve the precision of the processed parts, but the influence of several input technological parameters on all the deviations that appear in the deformed parts has not been intensively studied.

These previously mentioned aspects indicate the need to carry out an elaborate study on the possibilities of improving the dimensional and shape accuracy of the parts processed by incremental forming and the influence of the technological parameters in the process on it, with the aim of favoring the implementation of the process on a large scale in the industry.

Following the critical analysis of the current state in the field of incremental forming presented in chapters 2 and 3 of this PhD thesis, I made the decision together with the PhD supervisor to study methods for improving the dimensional and shape accuracy of incrementally formed parts. When carrying out this study, we opted for the use of two materials often encountered in the field of car construction: aluminum alloy AA1050 and DC01 steel.

We opted for initial research that would highlight the influence of the following process input parameters on the precision of incrementally formed parts: the final depth of the parts, the wall angle of the part, the vertical step of the toolpath and the diameter of the punch. In this stage we decided to use a space spiral toolpath which, according to the bibliographic study, favors obtaining a high precision of the deformed parts. Although there is a lot of research on the influence of these factors on part accuracy, they have been strictly oriented towards certain process output parameters. This doctoral thesis includes the study of the influence of the process input parameters on all the deviations highlighted during the research, namely:

- The deviation due to the material springback;
- The deviation due to the "cushion" effect;
- The deviation from the final depth of the part;
- The deviation from the diameter of the part;
- The deviation from the connection radius between the conical wall and the flange;
- The deviation from the part wall angle.

In addition, I decided in the second stage of the research to improve the dimensional and shape accuracy of the incrementally formed parts by using offline methods, which consist in the generation of complex part processing toolpaths.

Taking into account the critical analysis of the current state in the field and the considerations presented previously, together with the PhD supervisor I established the following objectives of the doctoral thesis:

1. Analysis and critical processing of information from the current state, with the aim of identifying: the materials that can be used in the incremental forming process, the shapes of the parts that can be processed, the technological parameters of the process;

2. Carrying out uniaxial tensile tests in order to determine the mechanical characteristics of materials to be used in finite element analysis programs;

3. Conception and development of a theoretical model for the numerical simulation of the incremental forming process using the finite element method;

4. Running explicit dynamic analyzes in order to validate the proposed theoretical model by comparing the results with those obtained experimentally;

5. Realization of a planning of the experiments by means of the Taguchi method; thus, we could consider all five input parameters without increasing the number of experiments;

6. Carrying out the experimental tests resulting from the planning to determine the deformations, the thinning of the material, the deformation forces, the roughness of the processed surfaces and all the dimensional and shape deviations previously mentioned;

7. Statistical analysis by means of the Taguchi method of the experimental data obtained through the Minitab software package;

8. Implementation of an algorithm in the finite element analysis program, ABAQUS CAE, in order to automate the running of numerical simulations, by adapting the theoretical model to each type of toolpath used;

9. Realization of some numerical simulations by means of the theoretical model developed to investigate the improvement of the precision of the parts by the implementation of some complex toolpaths;

10. Performing experimental tests using the results obtained from numerical simulations by using complex toolpaths;

11. Analysis and statistical processing of the results obtained from the second stage of experimental research.

Conclusions of the PhD thesis

The incremental forming process is intensively studied because of the advantages it has over conventional cold plastic deformation processes. It involves the use of a small number of components, namely thin sheet blanks of various materials, its fasteners and the tool represented by a punch, which travels a user-preset toolpath to deform the blank to the desired final shape.

The aim of this PhD thesis was to study how the technological parameters of the process influence the dimensional and shape accuracy of incrementally formed parts, on the one hand, and to propose and analyze methods to improve it. Following the bibliographic study, a multitude of variants proposed by the authors for the incremental forming process emerged. In this thesis, I chose to incrementally deform sheet metal blanks from aluminum alloy AA1050 and DC01 steel, two of the most commonly used materials in the car manufacturing industry. Even if aspects of the precision of incrementally formed parts are treated in the bibliographic literature, there is not yet an elaborated study that takes into account all the parameters entering the process (which can be divided into two large categories: technological parameters - the vertical step and punch diameter and geometric parameters - final part depth and part wall angle) and address the accuracy deviations identified in this thesis. After the bibliographic study I noticed that three deviations of the precision of the processed parts are treated: the deviation given by the springback, the deviation given by the connection radius between the wall of the part and the flange area and the deviation given by the "cushion" effect.

In addition to these deviations, in the framework of theoretical research and experimental tests, I studied three more deviations, namely: the deviation from the final depth of the part, the deviation from their desired diameter and the wall angle deviation. For the experimental tests I used sheets of 250 x 250 mm with a thickness of 0.8 mm for both materials.

In this PhD thesis, the experimental tests were focused on the determination of the dimensional and shape accuracy by analyzing the six deviations presented previously, the determination of the mechanical characteristics by the uniaxial test, the determination of the specific plastic strains of the material (main, secondary, deformations in the X and Y direction), shear angle, material thinning and deformation forces occurring during the process.

When carrying out the tests and measurements, I used the equipment provided by the Plastic Deformation Studies and Research Center of the "Lucian Blaga" University in Sibiu, namely: the Instron 5578 tensile testing machine, the KUKA KR210-2 industrial robot used for deforming the sheet blanks, equipped with PCB261A13 three-way force transducer, ARAMIS optical strain measurement system used during the process for image acquisition, ATOS CORE 3D optical measurement equipment used for measuring parts after the incremental forming process, and Surftest SJ-411 roughness tester used to measure surface roughness.

The experimental research was divided into two stages. In the first stage I analyzed how the punch diameter, vertical step, part wall angle, final depth of the part and the type of material influence the precision of the parts. For each influencing factor we used two levels of variation and for planning the experiments I used the Taguchi statistical method, also used to reduce the required number of experiments. When interpreting the results, I used the Minitab v19 software package, which allows the generation of signal/noise ratios with the condition imposed by the user, and in this case I used the condition "the smaller the better" because the purpose of this thesis was to reduce precision errors. In addition, the software package also allowed the generation of interactions between factors, in which case I analyzed the interactions between the technological parameters entering the process: punch diameter and vertical step. An advantage of using a statistical method for planning experiments is also given by the possibility of evaluating the measurements made by means of their normal distribution graph. When making the toolpaths, I used the SprutCAM X software package. I used the spatial spiral toolpath for all the experimental tests, because according to the bibliographic literature, they present uniform distributions of deformations.

All the tests were successfully carried out, with no material breakage defects reported, although in the case of the aluminum alloy, AA1050, the maximum strains obtained in the tensile test did not exceed 5%, compared to the steel, which has a high plasticity with deformations of more than 30%. After analyzing and interpreting all the results from the first stage, I determined that in the largest proportion the use of the punch with a diameter of 10 mm and the vertical step of 0.25 mm leads to obtaining the lowest values of the six analyzed deviations.

Following the experimental research in the first stage, I created a theoretical model of the process based on the finite element method. The results of the numerical simulations were analyzed and compared with the results obtained experimentally, and the differences were small, below 10%, thus the theoretical model was successfully validated. In order to carry out the numerical simulations of the proposed tests to improve the dimensional and shape accuracy, we developed an algorithm written in the Python language in order to automate the process of implementing complex toolpath from SprutCAM X in the finite element analysis software ABAQUS.

Through the developed theoretical model, I investigated an offline method for improving the precision of incrementally formed parts, which involved the correction of deviations by using complex part processing toolpaths. These toolpaths aim to correct the "cushion" effect by correcting the small base of the truncated cones, multi-pass machining to eliminate: deviations from the final depth, deviations from the diameter and angle of the part and the reduction of the deviation given by the material springback.

All these trajectories were also investigated experimentally in the second stage of the experimental research, where I used the full factorial planning, using two levels of variation for the material and six levels for the toolpath, one being the reference one - space spiral, and the other five being the proposed to improve accuracy. Following the theoretical and experimental research carried out in this thesis, I reached the following conclusions:

- the deviation given by the material springback decreases by using the aluminum alloy, the punch of 6 mm diameter and the wall angle of the part of 60°. In addition, the T3 toolpath being a multi-pass machining toolpath positively influences the springback;
- in the case of the deviation given by the "cushion" effect, it is strongly influenced by all the technological and geometric factors as follows: the use of the 10 mm punch, the vertical step of 0.25 mm, the wall angle of 50°, the depth of 40 mm and aluminum alloy helps to reduce this effect. From the point of view of the toolpaths, the T3 and T5 toolpaths contribute significantly to the reduction of this deviation;
- regarding the final depth of the parts, the minimum deviation values are obtained by using the punch of 10 mm diameter and the wall angle of 60° in the case of aluminum alloy. In terms of toolpaths, T1, T3 and T4 produce parts with the smallest deviations;
- the diameter of the part is influenced by the use of the punch of 6 mm diameter and the vertical step of 0.25 mm. However, the greatest influence is observed in the type of material where in the case of aluminum alloy more precise parts are obtained. Regarding the toolpaths proposed for improvement, the only one that brings an input is the T5 toolpath, which has a major influence on the precision of the parts, because being a toolpath in which the punch processes with an inclined axis, the errors given by the elasticity of the system formed by the robot, force transducer, punch and their fasteners are eliminated. When using this toolpath, the accuracy error is reduced by 90%;
- the deviation given by the connection radius between the part wall and the flange area is positively influenced by the use of the 10 mm diameter punch, the wall angle of 50° and the aluminum alloy. The toolpaths proposed for improvement also manage to make a contribution in this case, but it is not as significant as in the case of other deviations, because regardless of the toolpath used, by the nature of the incremental forming process, there is no element that provides support to the final product in the area in which the punch comes into contact with it;

- in order to obtain an wall angle of the part as precisely as possible, it is necessary to use the 10 mm diameter punch and the aluminum alloy, and the toolpath that produces significant improvements is also this time the T5 toolpath, with an inclined axis of the punch;
- considering the objectives of this thesis, I also analyzed the quality of the surfaces that came into contact with the punch, by measuring the R and W profiles, these being strongly influenced, as expected, by the diameter of the punch and the vertical step, and the use the larger diameter punch and the smaller vertical step led to a reduction in surface roughness.
- contrary to the previously studied deviations, where each time for the aluminum alloy, AA1050, lower values were obtained, in the case of roughness, they were lower in the case of the use of DC01 steel;
- in the case of the main specific strains, secondary specific strains and in the X and Y directions specific strains, they were strongly influenced by the wall angle of the part, and the maximum values were found in the parts with a wall angle of 60°. The other factors did not exert a strong influence on the strains;
- the complex toolpaths proposed to improve the precision exert significant influences on the strains, and the maximum values were obtained at the T3 toolpath, which is a machining toolpath through several passes. In the case of these complex toolpaths, it can be observed that the deformation distributions are not uniform on the parts, being located in different areas, depending on the type of toolpath used;
- as in the case of specific strains, the thinning of the material is also negatively influenced by the increase of the part wall angle, and the T3 toolpath produces major thinning of the part thickness;
- from the point of view of the forces measured during the process, they are approximately equal in the directions perpendicular to the axis of the punch and alternate from a minimum value to a maximum value equally spaced from 0, and the forces in the direction of the punch have a linear increase up to at some point after which then stabilizes and does not vary until the end of the incremental forming process;
- as expected, the maximum forces are most influenced by the type of material, and these were obtained in the case of DC01 steel, with values above 1 kN, unlike the aluminum alloy where values of approximately 300 N are recorded.

Original PhD Thesis Contributions:

Original contributions were published during the development of the PhD thesis in various ISI-Clarivate journals with impact factor, in journals indexed in international databases and in papers presented at scientific conferences. The original contributions of this thesis can be divided into two parts:

Original theoretical contributions:

- I carried out a bibliographic study of the process of single point incremental forming and extracted the main ideas regarding the different variants of the process proposed by other authors;
- I made a rigorous classification of the process and investigated the advantages and disadvantages of each variant of the process;
- I evaluated the technological parameters of the process regarding the types of material that can be processed, forming regimes, tools, fasteners and types of toolpaths used;
- I carried out a study on the technological equipment that can be used for the incremental forming process;
- I highlighted the advantages of the process compared to other classic plastic deformation processes (for example deep drawing), but also its limitations related to the low accuracy of the parts obtained and the long production time of a product;
- based on these considerations, I outlined the research niche, represented by the study of the dimensional and shape accuracy of the parts and the need to improve it, and I outlined the objectives of the thesis;
- I developed a theoretical model of the incremental forming process in the finite element analysis program, ABAQUS, which allows the analysis of the process and obtaining the necessary results in order to validate the model by comparing the results with those obtained experimentally and to research methods to improve the dimensional and shape accuracy;
- I designed and developed an algorithm in the Python programming language, for automating the process of implementing complex toolpaths in the finite element analysis program.

Original experimental contributions:

- I performed tensile tests for the studied materials, AA1050 aluminum alloy and DC01 steel, to determine their mechanical characteristics;
- I transformed the curves obtained from the tensile test into real curves, which describe the plastic behavior of the materials for their implementation in the numerical analysis software;
- I divided the experimental research into two stages: the first in which I analyzed the influence of the chosen factors on the accuracy of the parts from the point of view of six deviations identified in the produced parts, and in the second stage I proposed and analyzed an offline method for improving the dimensional and shape accuracy by implementing complex toolpaths of parts processed;
- I used statistical methods for planning experiments through the Taguchi method and factorial planning;
- I analyzed the graphs regarding the signal/noise ratios and the interactions between the technological parameters entering the process, the diameter of the punch and the vertical step;
- I prepared and adapted the equipment made available by the Plastic Deformation Studies and Research Center within the university for the investigation of the incremental forming process;
- I prepared and generated the toolpaths that the punch followed during the process and adapted them to be used on the KUKA industrial robot;
- I prepared all the data acquisition systems for the force transducer mounted on the robot and for the optical strain measurement system ARAMIS;
- I analyzed the results obtained from the acquisition of images of the parts in order to determine both the specific strains and the shear angle and the thinning of the material;
- I scanned 3D the parts obtained after the incremental forming process with the help of an ATOS CORE optical measuring equipment;
- I prepared a flexible support to be able to measure the quality of the surfaces in the contact area between the punch and the final product (on the conical wall) with the help of the Mitutoyo roughness tester.

Future research directions

Future research directions in the machine building industry, the replacement of classical plastic deformation processes, such as deep drawing, with new processes that allow greater flexibility, such as incremental forming, has been pursued for several years. But the big disadvantage of the incremental forming process is represented by the low accuracy of the processed parts, thus the topic of the PhD thesis falls within the current trends pursued by car manufacturers. Of course, there are also future research directions to take the incremental forming process one step closer to its widespread implementation in industry. I will list below some of the future research directions:

- carrying out a study of the accuracy of incrementally formed parts from other materials used or with the possibility of being used in the future in this industry, and here I refer to materials with improved mechanical properties, but with reduced weight, such as: magnesium and titanium alloys and the validation of their behavior regarding the accuracy deviations that appear as a result of the process;
- carrying out a study on the accuracy of parts made of polymeric materials or "sandwich" type panels;
- carrying out research that also takes into account other technological influencing factors, such as the travel speed of the punch and the speed of rotation around its own axis;
- the development of additional complex toolpaths compared to those presented in this thesis, aimed at processing parts with the punch inclined at a greater angle, so that it is perpendicular to the processed surface and to further reduce the errors given by the elasticity of the system;
- carrying out a study of the influence of different lubricants and how they affect the quality of the surfaces of the parts;
- designing and making a punch with a tip as small as possible to create the possibility of making the sharp edges that are found on car body elements;
- taking into account the dimensional and shape accuracy deviations of the parts processed by incremental forming and knowing the behavior during the process of as many types of materials as possible, the realization of a correction algorithm of the processed part from the design phase to reduce the accuracy deviations;
- the design and realization of another larger and flexible system for fixing final products, in order to process parts of the size of car body elements for the study of the possibilities of processing parts identical to those used in the automobile manufacturing industry.

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