Interdisciplinary doctoral school

PhD field: Industrial Engineering

PhD THESIS - ABSTRACT

Behaviour of welded sheet subjected to incremental forming

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CONTENT

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ABSTRACT

Sheet metal forming processes are important manufacturing processes used to produce components used in various civil and industrial sectors. The plastic deformation processes of sheets have the role of obtaining the desired shape of the parts without excessive thinning or the appearance of creases, and without removing chips. The plastic deformation of sheets can be achieved by conventional processes, such as: embossing, bending, lamination and others. To carry out the conventional methods of deformation of metal sheets, special, complex and expensive molds are needed, adapted to the desired shape of the part [SCH, 92]. In addition, it is necessary to use high-precision machining equipment for the production of parts. Therefore, conventional sheet metal forming processes are economical for medium, large series and mass production, because the cost of the dies is distributed among several products, leading to a significant reduction in tooling costs [ARF, 13].

Making quality parts in small manufacturing lots is a challenge for both conventional and non-conventional sheet metal forming processes. Due to these reasons and the importance of the deformation of sheet metal blanks in various industries, researchers show an increased interest in the development of new deformation methods, and they become more and more attractive with applicability in various fields. Non-conventional technologies include incremental sheet forming, which is extremely suitable for prototyping or one-of-a-kind production from an economic point of view [FIL, 02]. This method allows the creation of unique, complex products with asymmetrical shapes. The incremental sheet forming process leads to reduced production time and cost in prototyping and small series production.

In the industry of machine building, automotive manufacturing and other metal structures, welding is an essential and ubiquitous process. Welding provides an efficient way to join metal components, ensuring the strength and durability of the resulting structures. The use of welded blanks is widespread in industry to reduce the weight of parts without affecting their stiffness. The incremental sheet forming of welded sheets presents a new interest in the field, due to the advantages brought by the welding process. This allows more precise control of the shape and dimensions of the final part, eliminating the risk of over- or under-deformation of the part. This technique can also be applied to materials with varying properties, including steel, aluminum, copper, and special alloys. In conclusion, incremental sheet forming of welded sheets is an efficient and accurate method to deform welded metal blanks. By using this process, solid, reliable and durable structures can be obtained that meet stringent design and performance requirements. This technique continues to be developed and refined, contributing significantly to the advancement of the industry and related technologies.

Following the bibliographic study regarding the process of incremental sheet forming of welded sheets, the following can be noted:

- The welding process represents a non-demountable assembly of two or more components and presents advantages such as: reducing material consumption, making complex parts that cannot be obtained through other technological processes and obtaining tight joints;
- The welding process lends itself to small series and one-off production in various industries, such as: the automotive industry, the military industry, the chemical industry and the food industry;
- The classification of welding processes is extensive, and among the most frequently used are fusion welding processes. They involve melting the filler material and the edges of the base material joints under the influence of a heat source, resulting in a weld pool which, through crystallization, forms the welded seam (weld bead). One of the important parameters of the welding process is represented by the correct choice of the welding joint;
- Considering the process of incremental sheet forming of thin sheets and the difficulty of fusion welding sheets with thicknesses less than 1 mm, most researchers in the field have used the solid state friction welding process ("friction stir welding");
- Researchers in the field investigated the deformability of incremental sheet forming welded parts and observed that due to the welding process it decreases considerably. However, in the case of choosing optimal welding parameters regarding the tool rotation speed, its advance speed and the depth of penetration into the base material, numerous authors have managed to successfully deform the welded semi-finished products;
- In the case of aluminum alloys, several works have been developed that deal with the welding process by MIG/MAG, WIG or TIG and have demonstrated that using these processes it is possible to obtain incrementally deformed parts without the occurrence of material failure.

Following the current state achieved in the field of incremental sheet forming, presented in chapters 2 and 3 of this PhD thesis, I made the decision, together with the PhD supervisor, to study the incremental deformation behavior of welded sheets. When carrying out this study, we opted for the use of three materials often found in the field of automobile construction: aluminum alloy AA1050 and steels DC01 and S355.

Initially, I carried out a series of experimental tests to study the deformability of the three materials when they are incrementally formed, and I decided to keep the same technological parameters (tool diameter, advance speed, the type of trajectory used and the vertical step of the tool) for all the experimental tests carried out and to vary only the shape of the part, the angle of the part wall and its height. Thus, I chose to make parts with the shape of a truncated cone and a pyramid, with the fixed angle of the part wall of: 50°, 55° and with a variable angle of 40° to 75°, and the height of the parts to be: 40 mm, 30mm and 25mm. The study of the behavior of the basic materials during incremental sheet forming was carried out by analyzing the following results measured during the process:

- strains in the X direction (ε_x);
- strains in the Y direction (ε_y);
- major strains (ε_1);
- minor strains (ε_2);
- shear angle (γ);
- thickness reduction (s_{max});
- springback (R);
- the forces in the X, Y and Z directions (Fx, Fy și Fz).

In the second stage, I decided to study the incremental sheet forming behavior of the sheets welded by the processes: TIG, WIG and MAG. The measured results can be compared with those obtained in the previous stage and the influence of welding in the studied process will be observed.

Considering the current state achieved in the field and the previously presented considerations, I developed the following objectives of the phD thesis:

1. Analysis and processing of information from the current stage in order to identify: materials that can be used in the incremental sheet forming process as base materials, the shapes of the parts that can be processed, the optimal technological parameters of the process, the welding processes used for thin sheets;
2. Perform uniaxial tensile tests to determine mechanical properties of materials for use in finite element analysis programs as input data;
3. Carrying out uniaxial tests in order to verify the strength of the weld;
4. Conception and development of a theoretical model for the numerical simulation of the incremental sheet forming process by the finite element method;
5. Running explicit dynamic analyzes in order to validate the proposed theoretical model by comparing the results with those obtained experimentally;
6. Implementation of an algorithm in the finite element analysis program, ABAQUS, in order to automate the processing of the results to obtain the values of the material springback;
7. Realization of numerical simulations through the theoretical model developed to investigate the behavior of incrementally sheet forming welded sheets;
8. Realization of a planning of experiments by means of the Taguchi method;
9. Carrying out experimental tests resulting from the planning to determine the strains, thickness reduction, springback and deformation forces;
10. Statistical analysis and processing of data obtained experimentally with the help of the Taguchi method through the Minitab software package;

Conclusions of the phD thesis

The incremental sheet forming process is a process that is gaining popularity among researchers worldwide due to its high potential for manufacturing complex parts. To make it, a small number of components are used (the semi-finished sheet metal, its fixing elements and the tool that deforms the sheet), so a low cost of manufacturing a landmark is obtained compared to other classical deformation processes.

The aim of this PhD thesis is to study the behavior of incrementally formed unwelded and welded sheet metal semi-finished products and to analyze the deformability of the materials in the case of the researched process. In this thesis, I chose to incrementally form aluminum alloy sheets, AA1050, and steels, DC01 and S355, these being the most common materials in the automotive construction industry. In addition, I also chose to analyze the influence of different welding processes on sheets that were subsequently subjected to the incremental sheet forming process, thus verifying which of the welding processes presents the best deformability. Even if aspects of incrementally formed welded parts are treated in the specialized literature, there is not yet an elaborated study that compares the incremental sheet forming behavior of welded sheets through different welding processes, as well as the influence of the weld seam on the deformability welded sheets.

In the incremental sheet forming process, blanks with small thicknesses of up to 1 mm are usually used, due to the high deformation forces that occur during the process. Conversely, in the case of fusion welding processes, semi-finished products with thicknesses between 1 mm and 14 mm are used, which leads to the difficulty of studying the process of incremental deformation of welded sheets by conventional processes. Thus, in the specialized literature, most of the research has focused on the analysis of the process of incremental sheet forming of the welded plates through the solid state friction welding process ("friction stir welding") in order to combat this difficulty. In addition to the research up to now within this thesis I have tried to perform welding by conventional fusion welding processes of sheets with thicknesses of 0.8 mm, 0.9 mm and 1 mm.

In this phD thesis, the results of the experimental tests were focused on determining the influence of the weld bead on the deformability of the sheets and their behavior during the studied process, determining the mechanical characteristics of the unwelded specimens and validating the mechanical strength of the welds through the tensile test, determining plastic deformations of the material (major strains, minor strains, strains in the X and Y direction), shear angle, thickness reduction, springback 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 KR 210-2 industrial robot used at plate deformation equipped with PCB261A13 three-way force transducer and ARAMIS optical strain measurement system used during the process for image acquisition. In addition to this equipment, I used the Fronius MagicWave 4000 AC/DC TIG welding equipment and the DAIHEN DR ARK ROBO 1100 welding robot, located at the industrial partners SC Compa SA and EASY INDUSTRY SRL, to perform the welds.

As for the experimental research, it was divided into four stages. In the first stage, I analyzed the behavior of non-welded sheets under incremental sheet forming, and the technological factors were kept constant: the vertical step of 0.5 mm, the diameter of the tool of 10 mm, the advance speed of 0.04 m/s and the trajectory of the space spiral type. To study the behavior of non-welded sheets I decided to vary the angle of the part wall (50°, 55° and variable from 40° to 75°) and the thickness of the semi-finished products of 0.8 mm and 1 mm. To plan the experiments, I used the Taguchi statistical method, thus reducing the number of experiments. When interpreting the results I used the Minitab v19 software package that allows the generation of signal/noise ratios with the imposed condition, in this case I used the condition "the smaller the better" because it is desirable to obtain minimum values in the case of the studied results. The trajectories followed by the tool were made by means of the SprutCam software package, and they were of the space spiral type for all experimental trials.

Although in the tensile tests the aluminum alloy, AA1050, shows a small elongation at break, approximately 5%, the experimental tests were carried out without the appearance of material breakage due to the incremental sheet forming process that improves its properties due to complex stresses. After analyzing and interpreting all the results from the first stage of the experimental research, I noticed that parts with the aforementioned angles can be successfully deformed at a depth of 40 mm.

Following the experimental research in the first stage, I created a theoretical model of the incremental sheet forming 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 being less than 10%, the theoretical model is successfully validated. For easier processing of the result regarding the elastic recovery of the material, I designed and developed an algorithm written in the Python programming language to automate the process of exporting the sections necessary to calculate this result. Using the validated theoretical model, I carried out the numerical simulation of the process of incremental deformation of welded sheets with the help of the ABAQUS software package, in which case I used the following combinations of sheets: 0.8 – 0.8 mm, 0.8 – 1 mm and 1 – 1 mm, for all the proposed angles.

All these attempts were also investigated experimentally in the following three stages as follows: in the following two stages of the research of this thesis I used Taguchi experimental planning using two factors with three levels of variation each, and the welding processes were

TIG and WIG; in the last stage, I studied the behavior of unwelded and welded S355 semi-finished products using the MAG process.

Following the theoretical and experimental research in this phD thesis, I reached the following conclusions:

– Regarding the reference experimental tests presented in chapter 5, I performed 4 preliminary tests with the variable wall angle from 40° to 75° in order to determine the deformability of the material. These tests were successfully carried out, and following them I opted to carry out 8 more tests with constant angles of 50° and 55° made on AA1050 aluminum alloy and DC01 steel with thicknesses of 0.8 mm and 1 mm. Also, these tests were carried out without the appearance of the defect given by the breaking of the material and the deformations occurring during the process, the thickness reduction, the elastic recovery and the deformation forces were measured. These experimental tests represent the references for the study of the behavior of welded sheets through different processes.

– Following the reference experimental tests, I opted for the study of the behavior of TIG, WIG and MAG welded sheets.

– Although the TIG and WIG welding processes are similar, I have used different technological parameters when performing the welding processes, thus being treated in different chapters.

– In the case of experimental tests on sheets welded by the TIG process, I noticed from the tensile test that there is a possibility that the test pieces may break in the weld bead area due to the manual welding process, which can lead to the premature failure of the weld during incremental sheet forming process. However, I tried to carry out 9 experimental tests on welded sheets of DC01 steel, varying the combinations of thicknesses and the angle of the part wall. Initially, as in the reference tests, I made the variable angle pieces and observed that they yielded in the weld bead area, and the minimum depth of rupture was 32.31 mm. Thus, I excluded the experimental tests on parts with a wall angle of 55° and made the parts with a 50° angle. These have been successfully achieved without the occurrence of material failure, which means that TIG welded parts with a wall angle of 50° with a part height of 40 mm can be incrementally formed.

– After tensile tests on TIG-welded specimens I concluded that they have a stronger weld bead than the base material (DC01) due to the fact that no specimen broke in its area. This aspect allows the possibility to successfully perform the incremental deformation process. Thus, I planned 9 experimental trials as in the case of semi-finished products welded by TIG. From these experimental tests, the combination of thicknesses 0.8 – 0.8 mm did not withstand the process of incremental sheet forming, regardless of the angle of the wall of the part with a premature break at the depth of 11.5 mm. Instead, the other experimental tests carried out on the semi-finished products with the combinations of thicknesses 0.8 – 1 mm and 1 – 1 mm were successfully deformed, regardless of the angle used

– In addition to the DC01 welded blanks, I tried to perform the TIG welding process of the AA1050 aluminum alloy blanks, a process that I did either through a single pass or through a pass on both sides. After the welding process of this alloy, a weld seam with a lot of filler material was obtained. This is a major disadvantage in the incremental sheet forming process due to the excessive deformations that occur when the punch passes over the weld bead, a fact confirmed by the premature fracture in the weld bead area of all welded blanks in AA1050, regardless of the vertical pitch and diameter of the punch used.

– In the case of the experimental tests carried out on S355 steel semi-finished products welded by MAG, I observed the same behavior of the samples subjected to the tensile test as in the case of those welded by TIG, that is, they yielded in the area of the base material. For the study of the behavior of the welded semi-finished products under incremental sheet forming, we opted for the realization of two different shapes: a truncated cone and a truncated pyramid with a wall angle of 55° and their height of 30 mm. Similar to the TIG-welded AA1050 blanks, the weld was performed in one pass and two passes, respectively. Thus I concluded that the S355 semi-finished products welded by one pass did not withstand the incremental sheet forming process, instead those welded by two passes were successfully deformed.

– Following the research carried out in the framework of this phD thesis, I came to the conclusion that welded semi-finished products can be successfully incrementally deformed, but it depends a lot on the one hand on the technological parameters used in the welding process, respectively on the welding method and the experience of those who performs it.

In order to have an overview of the behavior of the sheets from the studied materials under incremental sheet forming, to synthesize the large volume of results and to be able to conclude the differences between the analyzed welding processes, I proposed to carry out an analysis that takes into account the behavior during processing. In this analysis I used the following symbols:

✔ it lasted until the end of processing

✘ it fail during processing

Tables 1 – 3 is presented the analyzes for the three materials: aluminum alloy (AA1050) and steels (DC01 and S355).

Table 1 – Analysis of the behavior of the sheets from DC01

Type of parts	Part wall angle	Sheet blank thickness [mm]	Behavior during processing
unwelded	variable	0.8	✔
		1	✔
	50°	0.8	✔
		1	✔
	55°	0.8	✔

Type of parts	Part wall angle	Sheet blank thickness [mm]	Behavior during processing
		1	✓
TIG welded	variable	0.8 – 0.8	✗
		0.8 – 1	✗
		1 – 1	✗
	50°	0.8 – 0.8	✓
		0.8 – 1	✓
		1 – 1	✓
	55°	0.8 – 0.8	✗
		0.8 – 1	✗
		1 – 1	✗
WIG welded	variable	0.8 – 0.8	✗
		0.8 – 1	✓
		1 – 1	✓
	50°	0.8 – 0.8	✗
		0.8 – 1	✓
		1 – 1	✓
	55°	0.8 – 0.8	✗
		0.8 – 1	✓
		1 – 1	✓

Table 2 – Analysis of the behavior of the sheets from AA1050

Type of parts	Part wall angle	Sheet blank thickness [mm]	Behavior during processing
unwelded	variable	0.8	✓
		1	✓
	50°	0.8	✓
		1	✓
	55°	0.8	✓
		1	✓
WIG welded through a pass on one side	55°	0.8 – 0.8	✗
		0.8 – 1	✗
		1 – 1	✗
WIG welded through a two-sided pass	55°	0.8 – 0.8	✗
		0.8 – 1	✗
		1 – 1	✗

Table 3 – Analysis of the behavior of the sheets from S355

Type of parts	The shape of the piece	Sheet blank thickness [mm]	Behavior during processing
unwelded	frustrum cone	0.9	✓
	frustrum pyramid		✓
MAG welded through a pass on one side	frustrum cone	0.9 – 0.9	✗
	frustrum pyramid		✗
MAG welded through a two-sided pass	frustrum cone	0.9 – 0.9	✓
	frustrum pyramid		✓

Original PhD Thesis Contributions

Taking into account the purpose of doctoral theses, which is to contribute new knowledge to the studied field, they are materialized through the original contributions of the doctoral thesis. These original contributions have been published during the elaboration of the doctoral thesis in various journals indexed in international databases with impact factor and in papers presented at scientific conferences.

In the case of this thesis, I have made the following original contributions:

– I conducted a bibliographic study of the incremental sheet forming process and extracted the main ideas regarding the various variants of the process proposed by other authors;

– I evaluated the technological parameters of the process regarding the types of materials that can be processed, deformation regimes, tools and equipment used, fastening elements, and types of trajectories employed;

– I conducted a bibliographic study of the thin sheet welding process and identified the main welding methods used for these materials;

– I performed a rigorous classification of fusion welding processes;

– I identified the optimal technological parameters used by other authors in the welding of thin sheets;

– I identified and analyzed the main issues that arise in the case of incremental sheet forming of thin sheets;

– based on these considerations, I outlined the research niche represented by the study of incremental sheet forming behavior of parts welded through classical fusion welding processes, as well as the need to investigate the possibility of incremental sheet forming of welded sheets. Subsequently, I set the objectives of the thesis;

– I developed a theoretical model of the incremental sheet forming process using the finite element analysis software ABAQUS. This model allows for the analysis of the process and obtaining the required results for validating the theoretical model by comparing them with experimental data, following the current industry trends;

– I implemented a method to simulate the welded semi-finished products subjected to incremental sheet forming to determine their deformation capabilities, aiming to reduce the number of experimental trials in line with the trend in the automotive industry;

– I designed and developed an algorithm in the Python programming language to automate the extraction of data required for determining material springback and implemented it in the interface of the finite element analysis software ABAQUS;

– I conducted the uniaxial tensile test for the studied materials: aluminum alloy AA1050, and steels DC01 and S355, to determine their mechanical properties;

– I verified the weld bead strength through the uniaxial tensile test of welded specimens with different thicknesses using the following processes: TIG, WIG, and MAG;

– I transformed the curves obtained from the uniaxial tensile test into true stress-strain curves for the plastic region of the materials to implement them in the finite element analysis software;

– I divided the experimental research into four stages: the study of the incremental sheet forming behavior of unwelded sheets, sheets welded with TIG, sheets welded with WIG, and sheets welded with MAG;

– I used statistical methods for experimental design through the Taguchi method;

– I analyzed the graphs concerning the signal-to-noise ratio and the interactions between combinations of sheet thicknesses and angles of truncated cone and pyramid-shaped parts;

– I prepared and adapted the stands provided by the Center for Studies and Research in Plastic Deformation within the university for investigating the incremental sheet forming process of welded sheets. Additionally, for the welding of thin sheets, I collaborated with industrial partners, utilizing their equipment;

– I prepared and generated the trajectories that the punch followed during the process and adapted them for use with the industrial robot KUKA KR210;

– I prepared all data acquisition systems for the force transducer mounted on the industrial robot and for the optical deformation measurement system ARAMIS;

– I analyzed the results obtained from the image acquisition of the parts to determine both the specific deformations and the shear angle and material thinning.

Future research directions

In the automotive manufacturing industry, there is a trend to replace traditional plastic deformation processes (such as deep drawing) with new processes that offer greater flexibility, such as incremental sheet forming. This process offers the advantage of high flexibility with reduced costs, aligning well with current trends. Presently, the demand for welded sheets is increasing, especially in the automotive industry. Incremental sheet forming is an economically efficient alternative for producing reinforcement, support, and structural elements within vehicles. Therefore, the doctoral thesis theme aligns perfectly with the current trends pursued by automotive manufacturers.

However, complex the study of incremental sheet forming of welded sheets presented in this doctoral thesis, there are still future research directions to improve the formability of welded sheets within this process. I will list some of the future research directions below:

- conducting an extensive study on the formability of welded sheets using classical fusion welding processes.
- implementing constitutive models in finite element analysis software to accurately describe the behavior of welded sheets.
- conducting a study to analyze the influence of all technological factors (punch diameter, lubricants used, vertical step, trajectory type, punch feed rate, and rotational speed) on the behavior of incrementally deformed welded sheets.
- developing complex trajectories that allow the production of parts with greater height and wall angle than those achieved in this doctoral thesis.

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