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PhD THESIS - ABSTRACT

INCREMENTAL FORMATION OF POLYMERIC MATERIALS

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KEYWORDS: incremental forming, polymeric materials, comparative analysis, finite element method, material model, influencing factor, punch diameter, forming step, wall angle, KUKA KR210-2, Aramis optical measurement system, forming forces, deformations, thinning, released temperature, precision

ABSTRACT

Technological developments in recent years have led to polymeric materials being increasingly used in areas such as automotive, aerospace and medical industries, hence the need for lower cost and environmentally friendly processing technologies and processes. One such process is the incremental forming process, which is relatively new compared to traditional forming processes, such as deep drawing or molding.

In recent years, there has been a growing interest in the incremental forming of polymeric materials due to their widespread use in industry and the increasing need for prototyping and one-offs, as well as parts in small series production. The automotive industry is one of the industries that has been looking for years to replace metal materials with lighter materials, as there has long been a quest to reduce vehicle mass and thus increase vehicle range. Also, due to the biocompatibility of some polymeric materials with the human body, various implants made of polymeric materials have been developed by incremental forming to replace implants from the same human body or from cadavers, thus minimizing the degree of rejection and the risk of infection.

Although studies on the behaviour of polymeric materials during cold plastic forming were started in the mid-1960s, studies on their behaviour during incremental forming started much later, only in 2008-2009. Despite the relatively recent emergence of the incremental forming process, it is currently only implemented in small and one-off series production for reasons of long processing times.

Most studies related to incremental forming behaviour have focused on the influence of a single parameter (forces, formability, precision of the parts obtained, etc.) and there are no studies to date that encompass the influence of all parameters

At the same time, there are few studies that analyze the deformations that occur in the incremental forming process of polymeric materials, most of them being based only on numerical simulation using the finite element method.

Also, there are few studies that comparatively analyze the behavior of several polymeric materials during the incremental forming process.

From the above considerations, the idea of the present PhD thesis was born, which aimed to study and comparatively analyze the incremental forming behavior of three polymeric materials, namely polyamide, polyethylene and polytetrafluoroethylene. Initially, the intention was to include polyoxymethylene in the study, but this material exhibited low elongation at break at ambient temperature, thus making it impossible to conduct the experiments and analyze them using this polymeric material.

Thus, in this doctoral thesis, I aimed to investigate the incremental forming behaviour both in terms of the material of the semi-finished product and in terms of the

influencing factors related to the part to be obtained, as well as the influencing factors related to the forming technology.

By carrying out most of the theoretical and experimental research in the Centre for Studies and Research of Metal Forming of the Faculty of Engineering in Sibiu, I have succeeded in completing a comprehensive study of the incremental forming process applied to polymeric materials at ambient temperature. These investigations were focused on the determination of the forming forces, of the strains and thinning of polymeric materials, of the temperatures released as a result of the self-heating process and on the precision of the parts obtained by the incremental forming process.

The theoretical and experimental research resulted in the publication of eight scientific papers published both in Clarivate Analytics listed or indexed journals and conference volumes and in journals indexed in international databases [159-166].

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Last but not least, the present thesis paves the way for research on the behaviour of other polymeric materials in the incremental forming process, the study of the behaviour of polymeric materials in the incremental forming process with local heating of the material or the punch, or the use of a numerically controlled machine instead of an industrial robot to increase the stiffness and therefore the precision of the parts obtained.

Chapter 2 presents the evolution and current state of the art in the scientific literature on the incremental forming process, from which the following possible research directions have emerged:

- Numerical simulation using the finite element method of the incremental forming process
- Experimental research on the forming behaviour of polymeric materials
- Improvement of the behaviour of polymeric materials during incremental forming
- Study of the influence of different process parameters (punch diameter and step in vertical direction) on the incremental forming process.
- Study of the influence of different geometrical parameters of incrementally formed parts (part wall angle and initial thickness of the blank) on the incremental forming process.

Since a significant percentage of the raw materials used in industry are polymeric materials, I have decided to review the development of research on polymeric materials using the incremental forming process in a separate chapter, namely Chapter 3.

Following the literature survey on the incremental forming process of polymeric materials, the following aspects emerged:

- The incremental forming of polymers occurs based on a combined plane and biaxial stretching stress, depending on the circumferential contact between the punch and the blank;
- The limitations of the incremental forming process of polymeric materials are

given by the occurrence of defects and material breakage;

- The formability of polymers is higher than that of metals, the maximum part wall angle being between 60^0 and 90^0, much greater than for metals and metal alloys;
- The forming forces vary over a wide range, between 190N and 1500N, depending on the type of material deformed and the process parameters;
- The feed rate is a parameter that does not influence the forming forces in the incremental forming of polymeric materials;
- The process parameters influence the forming forces differently, depending on the material used, and there is currently no agreement regarding their influence on the forming forces;
- The biggest advantages of the incremental forming process of polymers are the versatility, low forming forces and high deformation capacity (deformability);
- Springback is the biggest problem in the incremental forming of polymers, leading to very large dimensional and shape deviations;
- The low forming speed is another disadvantage of the incremental forming of polymers but also of metallic materials, which can be overcome by developing new incremental forming equipment allowing high speeds or by increasing the forming step. However, increasing the forming step leads to the use of a larger tool diameter which can result in lower surface quality but also in the prevention of premature defects.

All of the above points to the need for further research into incremental forming of polymers in the future in order to make this process industrially viable.

Based on the bibliographic studies presented in chapters 2 and 3 of my doctoral thesis, together with my supervisor, I decided to focus my theoretical and experimental research on the incremental forming at ambient temperature of four types of polymeric materials: polyamide 6 (PA6), high-density polyethylene (HDPE 1000), polytetrafluoroethylene (PTFE) and polyoxymethylene (POM-C). Of these, during the course of the experimental research, we eliminated one of the materials (polyoxymethylene) due to its low formability at ambient temperature. The following were selected as input parameters for the conducted research: material type, material thickness, wall angle of the processed part, forming step and punch diameter. The decision regarding the selection of the research in the present doctoral thesis was made taking into account the following:

- the incremental forming process is no longer considered a process with a very high degree of novelty, as its applicability in various branches of industry is already well implemented in small series and one-off productions;
- low-density materials are increasingly used in the automotive industry, the aeronautical and aerospace industries, the medical implant industry, etc. because they are light but display relatively good mechanical strength for their weight;
- although there are studies on the incremental forming behaviour of various

polymer materials, these studies have been strictly oriented towards a specific output parameter for the incremental forming process (forces, strains, precision of the part obtained, etc.), and there is no overall study encompassing them all;

- there are extremely few data that study the strains that occur in the incremental forming process of polymeric materials. Most of these studies are based only on the numerical simulation using the finite element method, which is why I wanted to conduct a study that allows the comparison of the results obtained numerically with those obtained experimentally;
- the existing studies have generally taken into account only 2-3 input parameters of the incremental forming process, whereas by using the Taguchi method as an experimental design method, I was able to take into account four parameters without significantly increasing the number of experiments. As it could be found in the literature, there are studies with contradictory results due to the fact that their authors could not take into account several factors and the interactions between them;
- there are very few comparative studies in the literature on the incremental forming behaviour of different types of polymeric materials, which is why I wanted to undertake such a study;
- the speed of the punch was removed from the usual input parameters for the incremental forming process because, unlike the case of metallic materials, it does not significantly influence the process for polymer materials.

In view of the above, and based on the bibliographic research presented in the two chapters related to the current state of the art in the field, I outlined the objectives of the doctoral thesis as follows:

1. Analysis and processing of the information contained in the current stage of incremental forming processing of polymeric materials with the aim of identifying: the types of materials that can be processed at ambient temperature, the geometric shape and dimensions of the polymeric parts that can be processed and the technological parameters that can be taken into consideration in the experimental research carried out during the doctoral thesis;
2. Selection of the optimal description of the polymeric material, based on its behaviour during the uniaxial tensile test, for use in numerical simulation analyses;
3. Design and running of explicit, parameterized dynamic analyses simulating the incremental forming process of polymeric materials;
4. Elaboration of a study containing the main output parameters for the incremental forming processing of polymeric materials, as well as their main influencing factors;
5. Experimental research on the elasto-plastic mechanical behaviour of the polymeric materials analysed;

6. Experimental research related to the determination of forces, strains, thinning, temperature released in the process and the precision of the parts obtained at the incremental forming of polymeric materials;
7. Statistical processing of the experimental data obtained with the aim of optimizing the forming process of polymeric materials in order to reduce the forces, deformations and thinning and to increase the precision of the parts and the temperature released, so as to improve the deformability of the material.

Chapter 4 presents the simulation of the incremental forming process of polymeric materials by means of the finite element method.

The following conclusions can be drawn from the analysis of the results obtained:

- Simulation by the finite element method of the incremental forming process of polymeric materials leads to results close to the experimental values obtained, with good agreement both in terms of the distribution of specific strains and thinning and in terms of their maximum values;
- The variation plots obtained by finite element simulation for the forces in the incremental forming process are extremely similar and the differences between the values obtained experimentally and those obtained numerically are small;
- When simulating the incremental forming process, for better accuracy of the results in terms of specific strains and thinning, it is recommended to use Ls-Dyna material model 24 for polyamide and material model 89 for polyethylene, whereas for better accuracy of the results in terms of process forces, it is recommended to use Ls-Dyna material model 89 for both types of materials;
- If the correct material model is used, the difference between experimental and simulation results for specific strain and thinning, excluding the secondary strain, is a maximum of 2.55% for polyamide and 4.21% for polyethylene, respectively;
- If the correct material model is used, the difference between experimental and simulation results for the forces, is a maximum of 2.54% for polyamide and 2.71% for polyethylene, respectively.

It can thus be concluded that the simulation of such a process can give very good results if the optimal input data for the analysis are chosen (density of the mesh, material model used, types of contacts, etc.), even if this simulation is very time consuming and depends on many factors.

Chapter 5 presents the determination of influencing factors in the experimental investigations of the incremental forming process of polymeric materials. For a more accurate evaluation, two research directions have been considered in this doctoral thesis: experimental research evaluating the deformation behaviour (formability) of these types of materials in general and experimental research strictly related to the incremental forming process of these types of materials.

Experimental investigations to determine the formability of these types of materials have focused on uniaxial tensile testing and biaxial tensile testing. I also chose this test because in incremental forming, the state of deformation is not uniaxial but is rather a plane state of deformation. The choice of the types of experiments was made taking into account not only the current state of the art in the field and the previous theoretical results, but also the practical, concrete possibilities available in the laboratories of the Centre for Studies and Research on Metal Forming and the Faculty of Engineering in Sibiu. Certainly, the large number of influencing factors of the incremental forming process, as well as the costs related to the research itself, were of particular importance in the finalization of the experimental plans. Thus, for the design of the experiment, I chose the Taguchi method which, with a reduced number of experiments, allows the achievement of very good results in terms of quality.

Following these considerations, we defined the following research directions related to the incremental forming process of polymeric materials:

- determination of the strains on two directions of the coordinate axes, the main and secondary specific strains, the shear angle and the material thinning;
- determination of the magnitude of the forces on the three directions of the coordinate axes in the incremental forming of polymeric materials;
- determination of the value of the temperatures of the parts occurring during the incremental forming process (temperatures due to the friction between the punch and the semi-finished product);
- evaluation of the precision of parts obtained by incremental forming of polymeric materials.

The rest of the chapter presents the machines and stands used to perform the experiments: the Instron 5587 uniaxial tensile and compression test machine, the experimental stand for biaxial tensile testing, the Kuka KR210-2 robot, the force measurement system, the blank clamping stand, the Aramis optical measurement system, the FLIR E6 thermal imaging camera and the Zeiss Metronom CT scanner.

Chapter 6 describes the experimental research on the formability of polymeric materials, namely uniaxial and biaxial tensile tests of polymeric materials. For the tensile test we chose four polymeric materials: polyamide 6 (PA6), high-density polyethylene (PEHD 1000), polyoxymethylene (POM-C) and polytetrafluoroethylene (PTFE) of two different thicknesses, 0.5 mm and 3 mm. The experimental data obtained were statistically processed using the Minitab 18 program [155], applying the Andreson-Darling test for normal distribution and the Grubbs test for determining outliers.

Statistical analyses of the experimental data obtained from the uniaxial tensile tests showed the following:

- no outliers were found for any of the measurements and a normal distribution of results was found for all the results obtained;
- the material with the highest value of the longitudinal elasticity modulus is polyoxymethylene (with an average value of 3063.56 MPa) and the material

with the lowest value of the elasticity modulus is polytetrafluoroethylene (with an average value of 478.14 MPa), which indicates that polytetrafluoroethylene has a significant elasticity;

- the yield strength, which is significant only for polyethylene, has an average value of 12.63 MPa, approximately 50% of the maximum value of the stress in the material;
- the material with the highest value for maximum stress is polyoxymethylene with 61.64 MPa, followed by polyamide with 41.54 MPa, polyethylene with 24.73 MPa and polytetrafluoroethylene with 22.83 MPa;
- the material with the highest elongation, estimated on the basis of the strain corresponding to the maximum stress, is polyethylene with 496.7%, followed by polytetrafluoroethylene with 344.23%, polyamide with 126.53% and polyoxymethylene with only 13.80%.

The biaxial tensile test was carried out using a stand designed and built a few years ago by a team of specialists from the Faculty of Engineering.

The experimental data obtained were statistically processed identically to those obtained from the uniaxial tensile tests and we concluded that there are no outliers and the data follow the normal distribution.

Following the analysis of the results and due to the fact that polyoxymethylene exhibits low elongations and increased resistance to deformation, I decided to eliminate this material from further research.

Chapter 7 presents the experimental research on the incremental forming process of polymeric materials as follows:

- experimental research to determine forces;
- experimental research to determine strains and thinning;
- experimental research to evaluate the temperature released;
- experimental research to evaluate dimensional accuracy.

The determination of forces during the incremental forming process of polymeric materials was performed by mounting on the arm of the Kuka KR210-2 robot arm a measurement system consisting of the PCB261A13 sensor, the CMD600 amplifier and the Quantum X MX840B acquisition system. Measurement system calibration was performed on the three axes of the system and then process verification was performed using the Instron 5587 tensile testing machine. The force-displacement curves thus measured showed a very good agreement between the values of the two measurements and therefore the validation of the force sensor calibration of the measuring system.

With the desire to apply as much stress as possible to the chosen materials, I carried out some preliminary experiments to observe whether all materials allow deformation and do not break at different values of the wall angle and different punch diameters.

Following these preliminary experiments, we made the decision to eliminate polytetrafluoroethylene from further research because it broke in each of the experiments.

The subsequent experiments were designed using the Taguchi orthogonal matrices, and regarding the forces in the forming processes, it is desired to obtain values as small as possible.

We have chosen four input parameters, two that are related to the part to be made, namely the material of the part and the wall angle of the part, and two that are related to the technological parameters, namely the diameter of the punch and the step in vertical direction. We thus obtained an experimental design with 18 levels: two levels of variation for the material (polyamide and polyethylene), three levels of variation for the wall angle of the part (50^0, 55^0 and 60^0), three levels of variation for the diameter of the punch (6, 8 and 10 mm) and also three levels of variation for the step (0.5, 0.75 and 1 mm).

The results obtained were interpreted using two statistical analyses: signal-to-noise ratios for forces (evaluation of the rank of each parameter considered) and analysis of variance for forces (evaluation of the contribution of each influencing factor and the interaction between the most important factors). We also used the regression analysis to find a relationship between the three response variables (α, Dp and p).

A number of conclusions can be drawn from the analysis of the results obtained from the measurement of forces during the incremental deformation of polymeric materials:

- The force in Oz direction (F_z) increases for both materials having local maxima and minima from the first contact of the punch with the blanksheet. The local maxima occur in the areas where the punch enters the material with a step and the minima occur in the moment preceding this moment. A slightly different behaviour is observed for the two different materials, in the case of polyamide the force increases after a steeper slope, reaching a maximum value somewhere around the middle of the working stroke after which it remains relatively constant or even decreases slightly when using punches with smaller diameters;

- Forces F_x and F_y have a variation somewhat similar to each other but different to the variation of force F_z;

- The maximum values of the forces are always higher for polyamide than for polyethylene for both the F_z force and the F_x and F_y forces.

- A study of the Taguchi and ANOVA analyses shows that both lead to the same conclusion: the most important influence on the maximum value of the force is that of the material, followed by the diameter of the punch, the vertical step and the angle of the wall of the part for all three types of forces, and it can therefore be concluded that the angle of the part has almost no influence on the values of the three types of forces;

- Force F_z decreases the smaller the diameter of the punch, the smaller the value of the step and the larger the value of the wall angle of the part;

- Forces F_x and F_y decrease the smaller the diameter of the punch, the smaller the value of the step and the value of the wall angle of the part. Basically, with the exception of the wall angle, which has an inverse influence on the F_x and F_y forces compared to F_z, the other parameters influence the forces in the same way.

- The optimal parameters that lead to a decrease in the value of force F_z are D_p= 6 mm, p = 0.5 mm and α = 60^0.

We also made two polyamide and polyethylene parts with a frustum of pyramid trajectory, obtaining the same conclusions as for the frustum of cone parts.

The determination of strains and thinning in the incremental forming process of polymeric materials was carried out using the Aramis optical measurement system by depositing a matt paint on the material and then depositing a fine powder of a matt black paint. The optical system measures, by acquiring successive images, determines the displacement of points on the part and then transforms them into strains and subsequently calculate the thinning.

The experimental design is identical to the one used for the determination of the forces, because the measurement of the forces was carried out simultaneously with the measurement of the strains and thinning.

The specific strains ε_x, ε_y, the major strain ε_1 and minor strain ε_2, the relative thinning s and the shear angle $_{xy}$ were determined. The results were analyzed based on the signal-to-noise ratios and the same "smaller is better" condition, noting that the wall angle has the greatest influence.

The results obtained were interpreted by means of two statistical analyses: signal-to-noise ratios for forces (evaluation of the rank of each parameter considered) and analysis of variance for forces (evaluation of the contribution of each influencing factor and the interaction between the most important factors). We also used the regression analysis to find a relationship between the three response variables (forces F_z, F_x and F_y) and the three input variables (α, Dp and p). The analysis of variance shows that the step and the material-step and material-punch diameter interactions have an insignificant contribution. The regression analysis shows that thinning only depends on the wall angle.

Frustum of pyramid shaped parts were also analyzed, and it was observed that all strains had higher values than for the frustum of cone shaped parts due to the geometry of the parts with linear edges which are concentrators for stresses and strains.

It was also observed that, in both materials, a twist of the material occurs around the Oz axis due to the low stiffness of these materials.

Comparing the deformation results, it can be noticed that the parts made of steel have the twist deformations lower than those made of polyamide or polyethylene, also due to the higher stiffness compared to those made of polymeric materials.

Due to the fact that polymeric materials undergo a temperature increase during the plastic forming process, we also treated this phenomenon in the case of polyamide and polyethylene in the incremental forming process. The experimental design was changed by eliminating the wall angle as an influencing factor because it had the least influence on the forces, and we introduced the material thickness as a parameter with a variation of all parameters on two levels. It was observed that the maximum temperatures obtained at the end of the incremental forming process were even above 100^0 C. From the analysis of the signal-to-noise ratios with the condition "higher is better" (heating the material contributes to the increased formability), it was found that the thickness of the material has the greatest influence on the temperature. The regression analysis shows that the diameter of the punch is the least significant factor.

In the case of cold forming processes, the main phenomenon that contributes to the reduction of the precision of the parts obtained is the springback of the part material after the effect of the forming forces has been removed.

Thus, I decided to conduct an experiment with four cases (repeated twice) for two different geometries (different part wall angles) of the two materials analyzed so far, namely polyamide and polyethylene. The angles selected were 55^0 and 60^0, material thickness g = 3 mm, step p = 0.75 mm and punch diameter Dp = 8 mm. The measurements were also made with the Aramis optical system capturing both the last position of the trajectory of the punch in the material and its position two minutes after its exit from the part. It was observed that the springback has significant values, which can be improved by optimizing the trajectory.

To prove that the material thickness measurements by the Aramis optical measurement system are good, we scanned the parts with a CT scanner and observed a good agreement with the data obtained by optical measurements.

The conclusions of the doctoral thesis

The purpose of this doctoral thesis was to identify the incremental forming behavior of polymeric materials. The incremental forming process is a relatively new process, in which the final shape of the part is obtained as a result of the displacement of the punch not only in one direction, but on a programmed trajectory, with components of the displacement in all three directions of the axes of the coordinate system. This incremental deformation process arose from the need to reduce the cost of dies and deformation equipment for small series and one-off production. Although research has been carried out on this forming process, most of this research has focused on the forming of metal sheets (steels, aluminium alloys, titanium alloys, etc.). There has also been early research on the deformation of certain plastics such as polyvinyl chloride, some types of polycarbonates and even polyamide or polyethylene. In the present thesis I have proposed to investigate the deformation behaviour not only in terms of the material of the semi-finished product, but also in terms of the influencing factors related to the part (shape of the part, wall angle, thickness of the semi-finished product) and the influencing factors related to the forming technology (punch diameter and step in vertical direction).

The results of the theoretical and experimental investigations were focused on determining: the forces in the forming process of polymeric materials, the strains and thinning of these materials, the temperatures released as a result of the friction between the punch and the semi-finished product and the precision of the parts obtained.

Following the theoretical and experimental investigations, we were able to reach the following conclusions:

- parts can be made by incremental forming for the automotive or consumer goods industry from polymeric materials with a height/diameter or height/width ratio of up to ½ at ambient temperature;
- a first limitation of the process consists in the fact that not all the polymeric materials analyzed in this thesis are suitable for the incremental forming process at ambient temperature and under the technological conditions imposed in this study. Therefore, polyoxymethylene and polytetrafluoroethylene cannot be processed by incremental forming at ambient temperature and a punch feed rate of 2400 mm/min;
- whereas in the case of polyoxymethylene it was to be expected that it would not be suitable for incremental forming, due to the fact that it had a low elongation at break even at uniaxial tensile testing, in the case of polytetrafluoroethylene, which has a high elongation at uniaxial tensile testing, it was observed that it does not resist biaxial and incremental forming, resulting in material breakage even in the early stages of the forming process;
- another limitation of the process is the particularly long processing times, which leads to the conclusion that this process is only economical for small series and one-off production, where the costs of the forming dies would not be amortized;
- theoretical research based on simulations using the finite element method approximated with very good precision the results obtained experimentally related to the variation of forces and deformations in the incremental forming of polymeric materials;
- the forces in the incremental forming process differ both in variation and in maximum values compared to the forces obtained during forming by other conventional processes for both polymeric and other materials. This is absolutely normal, as the forces occur in three directions and not in one, as is the case with conventional forming. The highest values are always those of the forces occurring in the vertical direction (in the direction of the penetration of the punch into the material) and the forces in the plane perpendicular to this direction have lower values, varying between a minimum and a maximum value located symmetrically with respect to 0. The forces in the vertical direction have local maxima whose values continue to increase until the end of the working stroke for polyethylene and until approximately half of the stroke for polyamide, respectively. Also, the maximum force values are higher for polyamide than for polyethylene;
- even though this incremental forming process substitutes to some extent conventional forming processes (deep drawing, for example), we found that the distribution of the main specific strains and thinning differs from their distribution in conventional processes. This is quite normal because the forming mode is different,

being achieved as a result of the punch travelling along programmed trajectories, and it is normal for the specific strains and thinning to have higher values along these trajectories. This is true for incremental forming processing of all materials, not just polymeric materials. The specific strains that occur in the case of polyethylene are smaller than those that occur in the case of polyamide under the same forming conditions;

- regarding the incremental forming of polymeric materials, due to the continuous friction between the punch and the material, an increase in temperature occurs along the trajectory followed by the punch;

- due to the phenomenon of springback, parts made of processed polymeric materials show deviations in shape and geometry, which are materialized by reducing the height of the part, changing the angle of the part wall and changing the connection radius between the part wall and its flange area;

- the most important of the influencing factors analyzed from the perspective of forces in the incremental forming process is the material of the semi-finished product. The deformation forces, either the force in the Oz direction or the other two in-plane forces, are higher if the material of the semi-finished product is polyamide than if the material of the blanksheet is polyethylene, of course, under the same deformation conditions;

- increasing the diameter of the punch leads to an increase in all deformation forces in the incremental forming process of polymeric materials;

- increasing the forming step also leads to to an increase in all deformation forces in the incremental forming process of polymeric materials;

- increasing the wall angle of the part leads to a decrease in the force in the Oz direction and an increase in the forces acting in the xOy plane during the incremental forming process of polymeric materials;

- the influencing factor with the most important contribution to the specific strains, thinning and shear angle is the part wall angle. As the value of the part wall angle increases, the values of the specific strains ε_x and ε_y also increase, the major strain ε_1 and the shear angle γ_{xy} increase and the minor specific strain ε_2 decreases;

- the material of the part also influences the strains in the sense that the specific strains ε_x and ε_y, the major strain ε_1 and the shear angle γ_{xy} are higher for polyamide than for polyethylene and the minor strain ε_2 is higher for polyethylene than for polyamide;

- as the diameter of the punch decreases, the values of the specific strains ε_x and ε_y increase, the value of the major strain ε_1 and of the shear angle γ_{xy} increases and the monior strain ε_2 decreases;

- for an average step value (0.75 mm) the values of the specific strains ε_x and ε_y decrease, the value of the major strain ε_1 and the minor strain ε_2 decreases and the value of the shear angle γ_{xy} increases;

- the most important influencing factor on the temperature due to friction between the punch and the material is the initial thickness of the semi-finished product.

Increasing the thickness of the semi-finished part leads to an increase in the temperature of the part in the incremental forming process;

- the temperature resulting from the friction between the punch and the material is always higher in the case of polyamide than in the case of polyethylene;
- with the decrease of the step in the forming process, the value of the temperature released in the forming process increases;
- the larger the diameter of the punch, due to the increase in contact area, the greater the frictional force and hence the higher the temperature value of the forming process;
- the geometric and dimensional deviations are greater in polyethylene parts than in polyamide parts due to the low stiffness of the material and the higher elasticity;
- the larger the wall angle of the part, the smaller the deviation in part height, the smaller the deviation in wall angle of the part and the larger the radius of connection between the tapered wall and the flange of the deformed part.

Future research directions

Some of the future research directions related to this forming process and these materials are:

- cold incremental forming processing of other types of polymeric materials, such as polycarbonate or composites made of polyamide or polyethylene reinforced with carbon or glass fiber;
- hot incremental forming, with local heating of the material on the side opposite to that on which the punch is acting;
- the study of the temperature released in the incremental forming process by taking into account other factors such as the roughness of the punch and the friction coefficient, materialized by the use of lubricants;
- conducting research that takes into account the speed of movement of the punch;
- the use of a numerically controlled machine instead of a robot or the use of a system on the robot that allows imprinting a rotary motion on the punch;
- the design of another clamping system that allows a smaller gap between the clamped edge of the blank and the actual processing area, in order to reduce the yielding of the blank and reduce deviations in incrementally formed parts;
- the use of another technological variant, considering that these polymer materials require relatively low forming forces.

REFERENCES

1 Afonso D, Alves de Sousa R, Torcato R. Integration of design rules and process modelling within SPIF technology-a review on the industrial dissemination of single point incremental forming. Int J Adv Manuf Technol. februarie 2018;94(9–12):4387–99.

2. Blaga A. Contribuții la deformarea incrementală a tablelor metalice subțiri, Teză de doctorat. Sibiu: Universitatea „Lucian Blaga”; 2011.

3. Li Y, Chen X, Liu Z, Sun J, Li F, Li J, et al. A review on the recent development of incremental sheet-forming process. Int J Adv Manuf Technol. septembrie 2017;92(5–8):2439–62.

4. Emmens WC, Sebastiani G, van den Boogaard AH. The technology of Incremental Sheet Forming—A brief review of the history. J Mater Process Technol. iunie 2010;210(8):981–97.

5. Leszak E. Apparatus and process for incremental deiless forming. US3342051A, 1967.

6. Berghahn GB, Murray JGF. Method of dielessly forming surfaces of revolution. US3316745A, 1965.

7. Iseki H, S. Sakamoto KK. Flexible and incremental sheet metal forming. În: Proc 40th JJCTP (in japoneza. 1989. p. 41-44,.

8. Matsubara S. Incremental backward bulge forming of a sheet metal with a hemispherical head tool: a study of a numerical control forming system. II J JSTP. 1994;1311-1316,.

9. Matsubara S. Method and device for forming metal plate. JP 07-132329, 1995.

10. Luttgeharm CA. Numerically controlled forming method. US6532786B1, US6748780B1, 2003.

11. Jeswiet J. Incremental single point forming. Trans North Am Manuf Res Inst SME. ianuarie 2000;29:75-79,.

12. Filice L, Fratini L, Micari F. Analysis of Material Formability in Incremental Forming. CIRP Ann. 2002;51(1):199–202.

13. Marabuto SR, Afonso D, Ferreira JAF, Melo FQ, Martins MABE, de Sousa RJA. Finding the Best Machine for SPIF Operations - a Brief Discussion. Key Eng Mater. martie 2011;473:861–8.

14. Bagudanch I, García-Romeu ML, Ferrer I, Ciurana J. Customized cranial implant manufactured by incremental sheet forming using a biocompatible polymer. Rapid Prototyp J. 2 ianuarie 2018;24(1):120–9.

15. Song T, Qiu ZY, Cui FZ. Biomaterials for reconstruction of cranial defects. Front Mater Sci. decembrie 2015;9(4):346–54.

16. Bonda DJ, Manjila S, Selman WR, Dean D. The Recent Revolution in the Design and Manufacture of Cranial Implants. Neurosurgery. 1 noiembrie 2015;77(5):814–24.

17. Ambrogio G, Sgambitterra E, De Napoli L, Gagliardi F, Fragomeni G, Piccininni A, et al. Performances Analysis of Titanium Prostheses Manufactured by Superplastic Forming and Incremental Forming. Procedia Eng. 2017;183:168–73.
18. Eksteen P. Development of incrementally formed patient-specific titanium knee prosthesis. Stellenbosch; 2013.
19. Sy LV. Modeling of Single Point Incremental Forming Process for Metal and Polymeric Sheet. Teză de doctorat. Universitatea din Padua; 2009.
20. Behera AK, de Sousa RA, Ingarao G, Oleksik V. Single point incremental forming: An assessment of the progress and technology trends from 2005 to 2015. J Manuf Process. iunie 2017;27:37–62.
21. Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J, Allwood J. Asymmetric Single Point Incremental Forming of Sheet Metal. CIRP Ann. 2005;54(2):88–114.
22. Amino M, Mizoguchi M, Terauchi Y, Maki T. Current Status of “Dieless” Amino’s Incremental Forming. Procedia Eng. 2014;81:54–62.
23. Ambrogio G, Gagliardi F, Bruschi S, Filice L. On the high-speed Single Point Incremental Forming of titanium alloys. CIRP Ann. 2013;62(1):243–6.
24. Hamilton K, Jeswiet J. Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences. CIRP Ann. 2010;59(1):311–4.
25. Sena JIVD. Advanced numerical framework to simulate incremental forming process [PhD Disserttion.,]. Universite de Liege and University of Aveiro; 2015.
26. Vanhove H, Mohammadi A, Guo YS, Duflou JR. High-Speed Single Point Incremental Forming of an Automotive Aluminium Alloy. Key Eng Mater. septembrie 2014;622–623:433–9.
27. Pereira Bastos RN, Alves de Sousa RJ, Fernandes Ferreira JA. Enhancing time efficiency on single point incremental forming processes. Int J Mater Form. noiembrie 2016;9(5):653–62.
28. Ham M, Powers BM, Loiselle J. Surface Topography from Single Point Incremental Forming Using an Acetal Tool. Key Eng Mater. aprilie 2013;549:84–91.
29. McAnulty T, Jeswiet J, Doolan M. Formability in single point incremental forming: A comparative analysis of the state of the art. CIRP J Manuf Sci Technol. ianuarie 2017;16:43–54.
30. Jeswiet J, Adams D, Doolan M, McAnulty T, Gupta P. Single point and asymmetric incremental forming. Adv Manuf. decembrie 2015;3(4):253–62.
31. Gupta P, Jeswiet J. Observations on Heat Generated in Single Point Incremental Forming. Procedia Eng. 2017;183:161–7.
32. Ziran X, Gao L, Hussain G, Cui Z. The performance of flat end and hemispherical end tools in single-point incremental forming. Int J Adv Manuf Technol. februarie 2010;46(9–12):1113–8.
33. Jeswiet J, Young D. Forming limit diagrams for single-point incremental forming of aluminium sheet. Proc Inst Mech Eng Part B J Eng Manuf. 1 aprilie 2005;219(4):359–64.

34. Hussain G, Gao L, Dar NU. An experimental study on some formability evaluation methods in negative incremental forming. J Mater Process Technol. mai 2007;186(1–3):45–53.
35. Suresh K, Bagade SD, Regalla SP. Deformation Behavior of Extra Deep Drawing Steel in Single-Point Incremental Forming. Mater Manuf Process. 3 octombrie 2015;30(10):1202–9.
36. Hussain G, Gao L, Hayat N, Qijian L. The effect of variation in the curvature of part on the formability in incremental forming: An experimental investigation. Int J Mach Tools Manuf. noiembrie 2007;47(14):2177–81.
37. Filice L, Ambrogio G, Micari F. On-Line Control of Single Point Incremental Forming Operations through Punch Force Monitoring. CIRP Ann. 2006;55(1):245–8.
38. Szekeres A, Ham M, Jeswiet J. Force Measurement in Pyramid Shaped Parts with a Spindle Mounted Force Sensor. Key Eng Mater. iulie 2007;344:551–8.
39. Hassan M, Hussain G, Wei H, Qadeer A, AlKahtani M. Progress on single-point incremental forming of polymers. Int J Adv Manuf Technol. mai 2021;114(1–2):1–26.
40. Nasulea D, Oancea G. Incremental deformation: A literature review. Bondrea I, Simion C, Inţă M, editori. MATEC Web Conf. 2017;121:03017.
41. Aerens R, Eyckens P, Van Bael A, Duflou JR. Force prediction for single point incremental forming deduced from experimental and FEM observations. Int J Adv Manuf Technol. februarie 2010;46(9–12):969–82.
42. Pérez-Santiago R, Bagudanch I, García-Romeu ML. Force Modeling in Single Point Incremental Forming of Variable Wall Angle Components. Key Eng Mater. martie 2011;473:833–40.
43. Eyckens P, Van Bael A, Aerens R, Duflou J, Van Houtte P. Small-scale Finite Element Modelling of the Plastic Deformation Zone in the Incremental Forming Process. Int J Mater Form. aprilie 2008;1(S1):1159–62.
44. Skjoedt M, Hancock MH, Bay N. Creating Helical Tool Paths for Single Point Incremental Forming. Key Eng Mater. iulie 2007;344:583–90.
45. Bambach M, Taleb Araghi B, Hirt G. Strategies to improve the geometric accuracy in asymmetric single point incremental forming. Prod Eng. iunie 2009;3(2):145–56.
46. Essa K, Hartley P. An assessment of various process strategies for improving precision in single point incremental forming. Int J Mater Form. decembrie 2011;4(4):401–12.
47. Duflou JR, Callebaut B, Verbert J, De Baerdemaeker H. Laser Assisted Incremental Forming: Formability and Accuracy Improvement. CIRP Ann. 2007;56(1):273–6.
48. Rauch M, Hascoet JY, Hamann JC, Plenel Y. Tool path programming optimization for incremental sheet forming applications. Comput-Aided Des. decembrie 2009;41(12):877–85.
49. Skjoedt M, Bay N, Endelt B, Ingarao G. Multi Stage Strategies for Single Point Incremental Forming of a Cup. Int J Mater Form. aprilie 2008;1(S1):1199–202.

50. Ambrogio G, De Napoli L, Filice L. A novel approach based on multiple back-drawing incremental forming to reduce geometry deviation. Int J Mater Form. august 2009;2(S1):9–12.
51. Allwood JM, Houghton NE, Jackson KP. The Design of an Incremental Sheet Forming Machine. Adv Mater Res. mai 2005;6–8:471–8.
52. Behera AK, Lauwers B, Duflou JR. Tool path generation framework for accurate manufacture of complex 3D sheet metal parts using single point incremental forming. Comput Ind. mai 2014;65(4):563–84.
53. Malhotra R, Reddy NV, Cao J. Automatic 3D Spiral Toolpath Generation for Single Point Incremental Forming. J Manuf Sci Eng. 1 decembrie 2010;132(6):061003.
54. Duflou JR, Verbert J, Belkassem B, Gu J, Sol H, Henrard C, et al. Process window enhancement for single point incremental forming through multi-step toolpaths. CIRP Ann. 2008;57(1):253–6.
55. Bambach M. A geometrical model of the kinematics of incremental sheet forming for the prediction of membrane strains and sheet thickness. J Mater Process Technol. septembrie 2010;210(12):1562–73.
56. Kim TJ, Yang DY. Improvement of formability for the incremental sheet metal forming process. Int J Mech Sci. iulie 2000;42(7):1271–86.
57. Young D, Jeswiet J. Wall thickness variations in single-point incremental forming. Proc Inst Mech Eng Part B J Eng Manuf. 1 noiembrie 2004;218(11):1453–9.
58. Micari F, Ambrogio G, Filice L. Shape and dimensional accuracy in Single Point Incremental Forming: State of the art and future trends. J Mater Process Technol. august 2007;191(1–3):390–5.
59. Malhotra R, Bhattacharya A, Kumar A, Reddy NV, Cao J. A new methodology for multi-pass single point incremental forming with mixed toolpaths. CIRP Ann. 2011;60(1):323–6.
60. Liu Z, Li Y, Meehan PA. Vertical Wall Formation and Material Flow Control for Incremental Sheet Forming by Revisiting Multistage Deformation Path Strategies. Mater Manuf Process. mai 2013;28(5):562–71.
61. Vanhove H, Gu J, Sol H, Duflou J. Process window extension for incremental forming through optimal work plane rotation. Spec Ed 10th Int Conf Technol Plast ICTP 2011. 1 ianuarie 2011;508–12.
62. Eyckens P, He S, Van Bael A, Van Houtte P, Duflou J. Forming Limit Predictions for the Serrated Strain Paths in Single Point Incremental Sheet Forming. În: AIP Conference Proceedings. Porto (Portugal): AIP; 2007. p. 141–6.
63. Bambach M, Hirt G. Performance Assessment of Element Formulations and Constitutive Laws for the Simulation of Incremental Sheet Forming (ISF). 1 ianuarie 2005;
64. Bambach M, Cannamela M, Azaouzi M, Hirt G, Batoz JL. Computer-Aided Tool Path Optimization for Single Point Incremental Sheet Forming. În: Advanced Methods in Material Forming. Berlin, Heidelberg: Springer Berlin Heidelberg; 2007. p. 233–50.

65. Yamashita M, Gotoh M, Atsumi SY. Numerical simulation of incremental forming of sheet metal. J Mater Process Technol. aprilie 2008;199(1–3):163–72.
66. Delamézière A, Yu Y, Robert C, Ayed LB, Nouari M, Batoz JL, et al. Numerical Simulation of Incremental Sheet Forming by Simplified Approach. În Paris, (France); 2011. p. 619–24.
67. Sebastiani G, Brosius A, Tekkaya AE, Homberg W, Kleiner M. Decoupled Simulation Method For Incremental Sheet Metal Forming. În: AIP Conference Proceedings. Porto (Portugal): AIP; 2007. p. 1501–6.
68. Hadoush A, van den Boogaard AH. Efficient implicit simulation of incremental sheet forming: EFFICIENT IMPLICIT SIMULATION OF INCREMENTAL SHEET FORMING. Int J Numer Methods Eng. 4 mai 2012;90(5):597–612.
69. Martins PAF, Kwiatkowski L, Franzen V, Tekkaya AE, Kleiner M. Single point incremental forming of polymers. CIRP Ann. 2009;58(1):229–32.
70. Barimani-Varandi A, Nasrabadi MK, Ravan BA, Javadi M. Rapid prototyping of aircraft canopy based on the incremental forming process. J Braz Soc Mech Sci Eng. februarie 2021;43(2):59.
71. Diabb Zavala JM, Leija Gutiérrez HM, Segura-Cárdenas E, Mamidi N, Morales-Avalos R, Villela-Castrejón J, et al. Manufacture and mechanical properties of knee implants using SWCNTs/UHMWPE composites. J Mech Behav Biomed Mater. august 2021;120:104554.
72. Duflou JR, Behera AK, Vanhove H, Bertol LS. Manufacture of Accurate Titanium Cranio-Facial Implants with High Forming Angle Using Single Point Incremental Forming. Key Eng Mater. aprilie 2013;549:223–30.
73. Bagudanch I, Lozano-Sánchez LM, Puigpinós L, Sabater M, Elizalde LE, Elías-Zúñiga A, et al. Manufacturing of Polymeric Biocompatible Cranial Geometry by Single Point Incremental Forming. Procedia Eng. 2015;132:267–73.
74. Vanhove H, Carette Y, Vancleef S, Duflou JR. Production of thin Shell Clavicle Implants through Single Point Incremental Forming. Procedia Eng. 2017;183:174–9.
75. Ambrogio G, Napoli LD, Filice L, M. Muzzupappa FG. Application of Incremental Forming process for high customised medical product manufacturing. J Mater Process Technol. 2005;162–163:156-162,.
76. Jackson KP, Allwood JM, Landert M. Incremental forming of sandwich panels. J Mater Process Technol. august 2008;204(1–3):290–303.
77. Ingarao G, Ambrogio G, Gagliardi F, Di Lorenzo R. A sustainability point of view on sheet metal forming operations: material wasting and energy consumption in incremental forming and stamping processes. J Clean Prod. iulie 2012;29–30:255–68.
78. Dittrich MA, Gutowski TG, Cao J, Roth JT, Xia ZC, Kiridena V, et al. Exergy analysis of incremental sheet forming. Prod Eng. aprilie 2012;6(2):169–77.
79. Silva MB, Marques T, Martins PAF. Single-point incremental forming of polymers. În: Mechatronics and Manufacturing Engineering. Elsevier; 2012. p. 293–331.

80. Groover MP. Fundamentals of modern manufacturing: materials, processes, and systems. Seventh edition. Hoboken, NJ: John Wiley & Sons, Inc; 2020. 1 p.
81. Feldman D. Polymer History. Des Monomers Polym. ianuarie 2008;11(1):1–15.
82. Scutaru MLuminiţa, Chiru A, Vlase S. Materiale plastice şi compozite în ingineria autovehiculelor. Ed. rev. şi adăug. Bucureşti: Matrix Rom; 2013.
83. Mocanu F. Elemente de elasticitate şi plasticitate. TEHNOPRESS. Iași; 2010.
84. Marciniak Z, Duncan JL, Hu SJ. Mechanics of sheet metal forming. 2nd ed. Oxford: Butterworth-Heinemann; 2002.
85. Deutsch I. Rezistența materialelor. a II-a revizuită. București: Editura Didactică și Pedagogică; 1979.
86. Whitney W, Andrews RD. Yielding of Glassy Polymers: Volume Effects. J Polym Sci. 1967;Part C(16):2981–90.
87. Ongchin L, Sternstein SS. Yield criteria for plastic deformation on glassy high polymers in general stress fields. În 1969.
88. O'Connell PA, McKenna GB. Yield and Crazing in Polymers. În: John Wiley & Sons, Inc., editor. Encyclopedia of Polymer Science and Technology. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2004. p. pst463.
89. Caddell RM, Raghava RS, Atkins AG. Pressure dependent yield criteria for polymers. Mater Sci Eng. februarie 1974;13(2):113–20.
90. Franzen V, Kwiatkowski L, Martins PAF, Tekkaya AE. Single point incremental forming of PVC. J Mater Process Technol. ianuarie 2009;209(1):462–9.
91. Lu K. The Future of Metals. Science. 16 aprilie 2010;328(5976):319–20.
92. Shaw MT. Cold Forming of Polymeric Materials. Annu Rev Mater Sci. august 1980;10(1):19–42.
93. Zhu H, Ou H, Popov A. Incremental sheet forming of thermoplastics: a review. Int J Adv Manuf Technol. noiembrie 2020;111(1–2):565–87.
94. Le VS, Ghiotti A, Lucchetta G. Preliminary Studies on Single Point Incremental Forming for Thermoplastic Materials. Int J Mater Form. aprilie 2008;1(S1):1179–82.
95. Franzen V, Kwiatkowski L, Neves J, Martins PAF, Tekkaya AE. On the capability of single point incremental forming for manufacturing polymer sheet parts. În: ICTP2008, 9th International Conference on Theory of Plasticity. 2008.
96. Silva MB, Alves LM, Martins PAF. Single point incremental forming of PVC: Experimental findings and theoretical interpretation. Eur J Mech - ASolids. iulie 2010;29(4):557–66.
97. Marques TA, Silva MB, Martins PAF. On the potential of single point incremental forming of sheet polymer parts. Int J Adv Manuf Technol. aprilie 2012;60(1–4):75–86.
98. Alkas Yonan S, Soyarslan C, Haupt P, Kwiatkowski L, Tekkaya AE. A simple finite strain non-linear visco-plastic model for thermoplastics and its application to the simulation of incremental cold forming of polyvinylchloride (PVC). Int J Mech Sci. ianuarie 2013;66:192–201.

99. Alkas Yonan S, Silva MB, Martins PAF, Tekkaya AE. Plastic flow and failure in single point incremental forming of PVC sheets. Express Polym Lett. 2014;8(5):301–11.
100. Bagudanch I, Garcia-Romeu ML, Centeno G, Elías-Zúñiga A, Ciurana J. Forming force and temperature effects on single point incremental forming of polyvinylchloride. J Mater Process Technol. mai 2015;219:221–9.
101. Rajenthirakumar D, Sridhar R. Single Point Incremental Sheet Forming of Polymer on Computer Numerically Controlled (CNC) Milling Machine Tool. Key Eng Mater. septembrie 2014;622–623:420–6.
102. Davarpanah MA, Mirkouei A, Yu X, Malhotra R, Pilla S. Effects of incremental depth and tool rotation on failure modes and microstructural properties in Single Point Incremental Forming of polymers. J Mater Process Technol. august 2015;222:287–300.
103. Bagudanch I, Garcia-Romeu ML, Sabater M. Incremental forming of polymers: process parameters selection from the perspective of electric energy consumption and cost. J Clean Prod. ianuarie 2016;112:1013–24.
104. Hussain G, Mahna A, Iqbal A. Response surface analysis of cold formability of polymers in Incremental Sheet Forming: Effect of parameters and associated thermal softening. Int J Precis Eng Manuf. mai 2016;17(5):613–21.
105. Lublasser E, Braumann J, Goldbach D, Brell-Çokcan S. Robotic Forming: Rapidly Generating 3D Forms and Structures through Incremental Forming. CAADRIA Proc. 2016;
106. Sridhar R, Rajenthirakumar D. Incremental Forming of Polymer-Numerical and Experimental Investigation. Polym Polym Compos. septembrie 2016;24(7):489–98.
107. Sridhar R, Rajenthirakumar D. Polymer Sheet Hot Incremental Forming - an Innovative Polymer Forming Approach. Polym Polym Compos. septembrie 2016;24(7):447–54.
108. Zhang XB, Wang J, Zhang SQ. Study on Process Parameters on Single Point Incremental Forming of PVC. Mater Sci Forum. noiembrie 2016;878:74–80.
109. Bagudanch I, Centeno G, Vallellano C, Garcia-Romeu ML. Revisiting formability and failure of polymeric sheets deformed by Single Point Incremental Forming. Polym Degrad Stab. octombrie 2017;144:366–77.
110. Conte R, Gagliardi F, Ambrogio G, Filice F, Russo P. Performance analysis of the incremental sheet forming on PMMA using a combined chemical and mechanical approach. În Penang, Malaysia; 2017. p. 080026.
111. Edwards WL, Grimm TJ, Ragai I, Roth JT. Optimum Process Parameters for Springback Reduction of Single Point Incrementally Formed Polycarbonate. Procedia Manuf. 2017;10:329–38.
112. Medina-Sánchez G, Torres-Jimenez E, Lopez-Garcia R, Dorado-Vicente R, Cazalla-Moral R. Temperature influence on Single Point Incremental Forming of PVC parts. Procedia Manuf. 2017;13:335–42.

113. Zha G cheng, Zhou X, Lu C kai, Zhao W, Sun S, Yan A xin, et al. Experimental study on the limit test method of polypropylene sheet incremental forming. Int J Adv Manuf Technol. noiembrie 2017;93(5–8):2369–74.
114. Clavijo-Chaparro SL, Iturbe-Ek J, Lozano-Sánchez LM, Sustaita AO, Elías-Zúñiga A. Plasticized and reinforced poly(methyl methacrylate) obtained by a dissolution-dispersion process for single point incremental forming: Enhanced formability towards the fabrication of cranial implants. Polym Test. iulie 2018;68:39–45.
115. Durante M, Formisano A, Lambiase F. Incremental forming of polycarbonate sheets. J Mater Process Technol. martie 2018;253:57–63.
116. Medina-Sanchez G, Garcia-Collado A, Carou D, Dorado-Vicente R. Force Prediction for Incremental Forming of Polymer Sheets. Materials. 3 septembrie 2018;11(9):1597.
117. Sabater M, Garcia-Romeu M, Vives-Mestres M, Ferrer I, Bagudanch I. Process Parameter Effects on Biocompatible Thermoplastic Sheets Produced by Incremental Forming. Materials. 8 august 2018;11(8):1377.
118. Ambrogio G, Gagliardi F, Conte R, Russo P. Feasibility analysis of hot incremental sheet forming process on thermoplastics. Int J Adv Manuf Technol. mai 2019;102(1–4):937–47.
119. Thangavel Karthik, DURAISWAMY Rajenthirakumar, NAGARAJAN Srinivasan, RAMASAMY Sridhar. Influence of Roller Ball Tool in Single Point Incremental Forming of Polymers. Teh Vjesn - Tech Gaz. februarie 2019;26(1).
120. Formisano A, Lambiase F, Durante M. Polymer self-heating during incremental forming. J Manuf Process. octombrie 2020;58:1189–99.
121. Durante M, Formisano A, Boccarusso L, Langella A. Influence of cold-rolling on incremental sheet forming of polycarbonate. Mater Manuf Process. 17 februarie 2020;35(3):328–36.
122. Hou C, Su X, Peng X, Wu X, Yang D. Thermal-Assisted Single Point Incremental Forming of Jute Fabric Reinforced Poly(lactic acid) Biocomposites. Fibers Polym. octombrie 2020;21(10):2373–9.
123. Ostasevicius V, Eidukynas D, Jurenas V, Paleviciute I, Gudauskis M, Grigaliunas V. Investigation of Advanced Robotized Polymer Sheet Incremental Forming Process. Sensors. 10 noiembrie 2021;21(22):7459.
124. Conte R, Ambrogio G, Pulice D, Gagliardi F, Filice L. Incremental Sheet Forming of a Composite Made of Thermoplastic Matrix and Glass-Fiber Reinforcement. Procedia Eng. 2017;207:819–24.
125. Okada M, Kato T, Otsu M, Tanaka H, Miura T. Development of optical-heating-assisted incremental forming method for carbon fiber reinforced thermoplastic sheet—Forming characteristics in simple spot-forming and two-dimensional sheet-fed forming. J Mater Process Technol. iunie 2018;256:145–53.
126. Bagudanch I, Vives-Mestres M, Sabater M, Garcia-Romeu ML. Polymer incremental sheet forming process: Temperature analysis using response surface methodology. Mater Manuf Process. 2 ianuarie 2017;32(1):44–53.

127. Silva MB, Skjoedt M, Martins PAF, Bay N. Revisiting the fundamentals of single point incremental forming by means of membrane analysis. Int J Mach Tools Manuf. ianuarie 2008;48(1):73–83.
128. Silva MB, Skjoedt M, Atkins AG, Bay N, Martins PAF. Single-point incremental forming and formability—failure diagrams. J Strain Anal Eng Des. 1 ianuarie 2008;43(1):15–35.
129. Kumar AL, Reddy KB. Experimental investigation of incremental sheet metal forming on polyvinylchloride (PVC) by using CNC vertical milling machine. În 2016.
130. Lozano-Sánchez L, Bagudanch I, Sustaita A, Iturbe-Ek J, Elizalde L, Garcia-Romeu M, et al. Single-Point Incremental Forming of Two Biocompatible Polymers: An Insight into Their Thermal and Structural Properties. Polymers. 1 aprilie 2018;10(4):391.
131. Ai S, Long H. A review on material fracture mechanism in incremental sheet forming. Int J Adv Manuf Technol. septembrie 2019;104(1–4):33–61.
132. Al-Ghamdi KA. Spring back analysis in incremental forming of polypropylene sheet: An experimental study. J Mech Sci Technol. octombrie 2018;32(10):4859–69.
133. Duflou JR, Sutherland JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, et al. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Ann. 2012;61(2):587–609.
134. Branker K. A study of energy, carbon dioxide emissions and economics in machining: milling and single point incremental forming. Queen’s University (Canada); 2011.
135. Centeno G, Morales-Palma D, Gonzalez-Perez-Somarriba B, Bagudanch I, Egea-Guerrero JJ, Gonzalez-Perez LM, et al. A functional methodology on the manufacturing of customized polymeric cranial prostheses from CAT using SPIF. Rapid Prototyp J. 20 iunie 2017;23(4):771–80.
136. Centeno G, Bagudanch I, Morales-Palma D, García-Romeu ML, Gonzalez-Perez-Somarriba B, Martinez-Donaire AJ, et al. Recent Approaches for the Manufacturing of Polymeric Cranial Prostheses by Incremental Sheet Forming. Procedia Eng. 2017;183:180–7.
137. Zienkiewicz OC, Taylor RL. The Finite Element Method. 5-lea ed. Vol. 1. Butterworth-Heinemann; 2000.
138. Leoveanu IS, Tierean MH. Metode numerice avansate. Aplicatii in modelarea metalelor. Universitatea Transilvania din Brasov; 2009.
139. Owen DRJ. Finite Element In Plasticity: Theory and Practice. Pineridge Press Limited; 1980.
140. Katsikadelis JT. The boundary element method for engineers and scientists: theory and applications. Second edition. London: Academic Press; 2016. 446 p.
141. LS-DYNA Keyword User’s Manual, Version R7.0. Vol. I, II, III. 2013.
142. Dușe DM, Cofaru NF. Bazele cercetării experimentale. Sibiu; 2001.
143. Ungureanu I. Bazele cercetării experimentale. Editura Universității din Pitești; 2002.

144. Oleksik M. Cercetări teoretice și experimentale privind comportarea mecanică a materialelor compozite cu suport textil. [Sibiu]: Universitatea „Lucian Blaga” din Sibiu; 2014.
145. KUKA High Payload Robot Series [Internet]. Disponibil la: https://www.robots.com/robots/kuka-kr-210
146. KUKA KR C2 Controller [Internet]. RobotWorx. [citat 28 septembrie 2022]. Disponibil la: https://robots.com/controllers/kuka-kr-c2-controller
147. SprutCAM Tech | Multipurpose CAD/CAM solutions | CAD/CAM softwareЫ [Internet]. sprutcam.com. [citat 28 septembrie 2022]. Disponibil la: https://sprutcam.com/
148. PCB261A13 [Internet]. Disponibil la: http://pcbpiezotronics.co.uk/contentstore/docs/PCB_Corporate/ForceTorque/Products/Manuals/261A13.pdf
149. CMD600 Data sheet [Internet]. Disponibil la: http://www.sensor-hbm.com/upload/product-file/b2823.pdf
150. QuantumX MX840B/MX440B: Universal Data Acquisition Module [Internet]. HBM. 2022 [citat 23 septembrie 2022]. Disponibil la: https://www.hbm.com/en/2129/quantumx-mx840b-8-channel-universal-amplifier/
151. ARAMIS Multi Sensor: Measure all around strains and displacements [Internet]. [citat 28 septembrie 2022]. Disponibil la: https://www.gom.com/en/topics/aramis-multisensor-dic-systems
152. FLIR E6-XT Infrared Camera with Extended Temperature Range | Teledyne FLIR [Internet]. [citat 28 septembrie 2022]. Disponibil la: https://www.flir.eu/products/e6-xt?vertical=condition+monitoring&segment=solutions
153. GOM Inspect Pro: Making quality easily visible | Software for 3D inspections [Internet]. [citat 28 septembrie 2022]. Disponibil la: https://www.gom.com/en/products/zeiss-quality-suite/gom-inspect-pro
154. ZEISS METROTOM [Internet]. [citat 23 septembrie 2022]. Disponibil la: https://www.zeiss.com/metrology/products/systems/computed-tomography/metrotom.html
155. Data Analysis, Statistical & Process Improvement Tools [Internet]. wwwSite. [citat 28 septembrie 2022]. Disponibil la: https://www.minitab.com/content/www/websites/en-us.html
156. The Anderson-Darling statistic [Internet]. [citat 28 septembrie 2022]. Disponibil la: https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistics/basic-statistics/supporting-topics/normality/the-anderson-darling-statistic/
157. Stephanie. Grubbs’ Test for Outliers (Maximum Normed Residual Test) [Internet]. Statistics How To. 2016 [citat 28 septembrie 2022]. Disponibil la: https://www.statisticshowto.com/grubbs-test/

158. CMD Charge Amplifier for Piezoelectric Sensors [Internet]. HBM. 2020 [citat 28 septembrie 2022]. Disponibil la: https://www.hbm.com/en/2659/paceline-cmd-digital-charge-amplifier/
159. Rosca N, Trzepieciński T, Oleksik V. Minimizing the Forces in the Single Point Incremental Forming Process of Polymeric Materials Using Taguchi Design of Experiments and Analysis of Variance. Materials. 17 septembrie 2022;15(18):6453.
160. Rosca N, Oleksik M, Rosca L. Numerical-Experimental Study Regarding the Single Point Incremental Forming Process. Cofaru NF, Inţă M, editori. MATEC Web Conf. 2021;343:03008.
161. Rosca N, Oleksik M, Oleksik V. Experimental Study Regarding PA and PE Sheets on Single Point Incremental Forming Process. Cofaru NF, Inţă M, editori. MATEC Web Conf. 2021;343:03009.
162. Rosca NA. A Succint Review Of Single Point Incremental Forming Of Polymers. ACTA Univ Cibiniensis Tech Ser. 2021;Technical Series(73:1-5).
163. Rosca N, Oleksik V, Pascu A, Oleksik M, Avrigean E. Optical study for springback prediction, thickness reduction and forces variations on single point incremental forming. Mater Today Proc. 2019;12:213–8.
164. Roşca NA, Oleksik M. Simulation of the Single Point Incremental Forming of Polyamide and Polyethylene Sheets. Bondrea I, Cofaru NF, Inţă M, editori. MATEC Web Conf. 2019;290:03014.
165. Pascu A, Oleksik M, Roşca N, Avrigean E, Oleksik V. Experimental studies on uniaxial and echibiaxial tensile tests applied to plastic materials sheets. Mater Today Proc. 2019;12:271–8.
166. Rosca NA. A Brief Review of Manufacturing Medical Implants by Single Point Incremental Forming. ACTA Univ Cibiniensis. 1 decembrie 2018;70(1