UNIVERSITATEA LUCIAN BLAGA DIN SIBIU

Interdisciplinary doctoral school
PhD field: INDUSTRIAL ENGINEERING

PhD THESIS - ABSTRACT

STUDIES AND RESEARCH REGARDING THE USE OF INDUSTRIAL ROBOTS IN PLASTIC DEFORMATION PROCESSES

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SIBIU 2022

SUMMARY

This PhD thesis entitled “Studies and research regarding the use of industrial robots in plastic deformation processes” includes:

- 6 chapters, preceded by an introductory section;
- 17 tables;
- 80 equations;
- 82 figures;
- 193 references.

The research directions approached in this PhD thesis, that emerged from the analysis and synthesis of the current state, are structured in two parts: theoretical research and experimental research.

The theoretical and experimental research was carried out between 2017 and 2022, within the Metal Forming Research Centre of the “Lucian Blaga” University of Sibiu.

KEYWORDS: mechanical process, incremental forming, industrial robot, energy consumption, finite element analysis, flexible manufacturing system, CAD, CAM, CAE, major and minor strain, equivalent Von Mises strain, thickness reduction, forming forces, innovation trajectories, geometric dimensioning and tolerancing, KUKA KR 210-2, relative position, differential torques, kinematic joint.

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INTRODUCTION

Economic and social developments, often linked to the impact of the digital revolution, the energy transition and globalisation, are taking place in all fields of activity. Globalisation has created new opportunities, posing a challenge for the industry. Industrial companies are being forced to improve their production systems, so that they can react quickly and cost-effectively to unpredictable market conditions.

On the other hand, the global economic and financial crisis, together with the health crisis, forced companies to rethink their production strategies and invest in highly innovative processing technologies.

If until recently the use of an industrial robot on a manufacturing line was only accessible to large companies, it is now accessible to organisations of all sizes, including SMEs. Given that industrial robots can be programmed to perform dangerous, strenuous and/or repetitive tasks with high precision, they are increasingly used in a wide variety of industries and applications.

Subtractive manufacturing, together with metal forming processes, are the most widespread and widely used methods of generating the shape of finished parts with applications in the automotive, aeronautics, electronics and electrical engineering, consumer goods and food industries.

There was a clear distinction between the two main groups of machining processes, but more recently, due to technological developments and economic conditions, research into subtractive manufacturing or metal forming processes has greatly extended their area of application.

Given the obvious trend towards product customisation, increasing the flexibility of metal forming processes has been an intensely debated topic in industry, in recent years. It is well known that conventional sheet-metal forming manufacturing processes allow the production of large series and mass-produced parts, providing a high level of production automation, but still achieving a low level of flexibility. In the case of small or one-off series production of sheet metal parts, the extremely high costs of press or die have a negative impact on production.

When processing a small to medium batch of parts using incremental forming process, costs and development time are significantly reduced compared to using conventional sheet-metal forming manufacturing processes. The process has a high degree of flexibility, since by using different trajectories, but using the same punch and the same active plates, a variety of hollow shapes can be obtained.

Considering the simplicity of the kinematics of the incremental forming process, it can be performed on various industrial equipment (specialised machines, CNC milling machine tools, industrial robots, etc.). Given the high rigidity, the main equipment used for incremental forming is the CNC machine tools. Due to the high flexibility and high travel speeds, an alternative to CNC machine tools could be industrial robots. The incremental forming process is known to be slow, and the high travel speed of an industrial robot can compensate for this disadvantage. Additionally, the high flexibility of an industrial robot allows complex shaped parts to be produced with high precision.

Many robots operate on production lines, where the highest percentage of energy is consumed. For instance, in automotive industries, the energy consumption of industrial robots is about 8% of the total energy consumption in the production phase [128]. Energy is an essential component in the economic development and for the progress of society in general. A specific objective in national and European energy efficiency action plans is to reduce energy consumption by industrial consumers [186].

Therefore, reducing energy consumption has become a major topic for many robot manufacturers and for academic research groups. However, reducing the consumption is still a challenging task that requires a deep understanding of the kinematic and dynamic behaviour of the technological equipment used in the machining processes.

TARGET AND PROCEDURE

Based on the above-mentioned, this PhD thesis focuses on the study of the use of industrial robots in an incremental forming process, on improving the energy consumption of the robot machining process, as well as on the dimensional and shape accuracy of parts processed by developing integrated kinematic and dynamic models.

The topic of the PhD thesis is part of the interests of the Metal Forming Research Centre of the "Lucian Blaga" University of Sibiu and was approached in order to research aspects related to the use of serial topology robots as technological equipment in the process of single-point incremental forming.

After a critical analysis of the literature on the incremental forming process and on industrial serial robots, the present work focuses on the development of an algorithm for establishing the energy consumption during the incremental forming process, using the industrial robot KUKA KR 210-2. A reduced energy consumption of the technological equipment during the process could lead to an increase in the dimensional and shape accuracy of the obtained parts [89, 90]. The steps taken to develop the algorithm are represented graphically in the figure below.

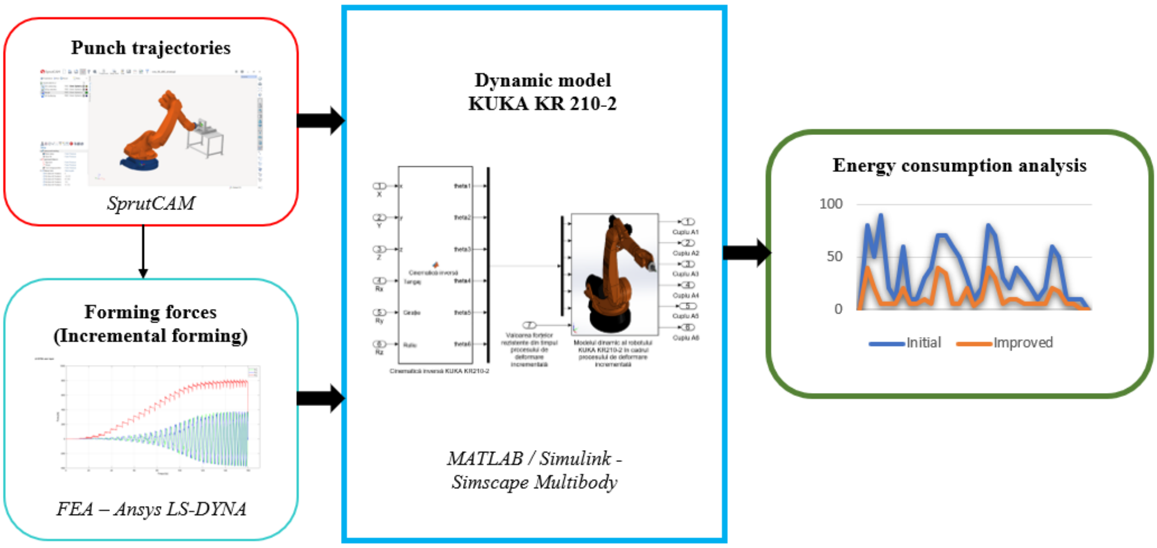

Fig. I: Block diagram corresponding to the development of the algorithm for establishing energy consumption.

In order to achieve the main objective, several research directions have been defined and are presented below.

A first research direction was the development of innovative trajectories that need to be followed by the punch in order to generate the final shape of the part. These trajectories were realised in a computer aided manufacturing (CAM) software, SprutCAM. Once the trajectories of the punch are established, they will be the input data for the dynamic model developed in the thesis, as well as for the finite element method (FEM) analyses.

The second research direction was both the determination of the forming forces, and the determination of minor and major strain and of the thickness reduction during the forming process. In order to develop practical, efficient and fast methods to determine the forces that occur during the incremental forming process, a model was developed, in order to allow process analysis by FEM. The verification of this analysis model using FEM was carried out by comparing the results obtained by simulation with those obtained experimentally. The verification block diagram of the analysis model using FEM is shown in the figure below.

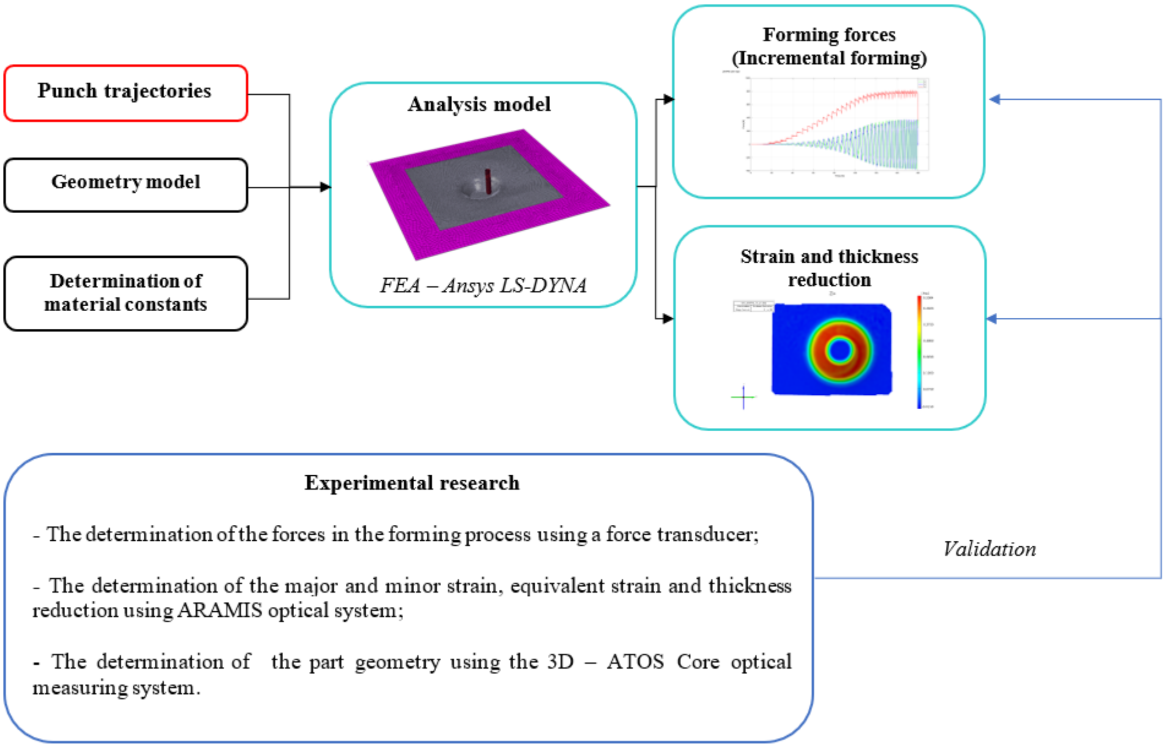

Fig. II: Validation block diagram of the analysis model using FEM.

Once the FEM analysis model is validated, it will allow the determination of forces in the machining processes, with no need for experimental determinations. Thus, by modifying the process characteristics (geometry model, material constants, user-imposed trajectories), the values of the forming forces can be determined based on the FEM simulation. These values will be used as input data in the dynamic model of the KUKA KR 210-2 robot used in the incremental forming process.

Once the trajectories to be traversed by the punch in order to obtain the final shape of the part and the forces during the process have been obtained, the dynamic model of the entire incremental forming process using the robot was created in the Matlab/Simulink - Simscape-Multibody environment.

Within the developed dynamic model, by including the user-imposed trajectory and the values of the forming forces, the values of the resisting torques of the kinematic joint of the robot during the incremental forming process can be determined. For the same imposed trajectory, by choosing a robot configuration or by changing the position of the metal sheet in the robot workspace, reduced resisting torques can be obtained. Achieving low resisting torques leads to low energy consumption.

To develop the dynamic model of the robot, a first step was to solve the kinematic problem of the KUKA KR 210-2 serial topology robot. Solving the kinematic problem offers the possibility to drive the robot along a user-imposed trajectory. Addressing the above-mentioned problem starts by solving the inverse kinematic problem. The inverse kinematic problem is concerned with determining the relative positions between the kinematic elements of the robot, if the imposed trajectory of the punch is known. Solving inverse kinematics is usually a difficult step that requires in-depth analysis. In the present case, for the robot under study, the analytical method was used as a method for solving inverse kinematics. The next step in creating the dynamic model was to develop the virtual model of the robot in the Simulink-Simscape-Multibody environment. The development of the virtual model of the robot in Simulink-Simscape-Multibody was achieved by importing the three-dimensional (3D) model of the KUKA KR 210-2 robot from a computer-aided design (CAD) software, into Simulink. The CAD model of the robot was taken from the KUKA industrial robot manufacturer's website, observing the mechanical characteristics of the real KUKA KR 210-2 robot. These characteristics relate to the mass of moving elements, moments of inertia, element lengths and centres of gravity. By importing the CAD model into Simulink-Simscape, all the mechanical characteristics of the robot were imported: element dimensions, coordinate systems, vector relationships between elements, their mass and volume, gravitational forces and moments of inertia. Various simulations of the incremental forming process were performed to determine the resisting torques. As a result of these simulations, the resistive torques of the kinematic joint of the KUKA KR 210-2 robot during the incremental forming process were determined. However, since not all the mechanical properties of the robot structure are known precisely, to overcome this impediment, it was decided to determine the difference between the values of the resistive torques measured under load and measured at idle. Thus, by using this calculation, only the dynamic effects due to the process, additional moments were considered, removing from the system the influence of the centre of mass and the moment of inertia of the robotic structure, which are not precisely known.

The fourth research direction was to carry out research on improving the dimensional and geometric (form) accuracy of the obtained parts by reducing the loads on the robotic structure. Trajectory planning is one of the important aspects of control, representing a fundamental problem in robotics. A well-planned trajectory guarantees good path following and places less stress on the mechanical structure of the robot, so that the quality of the machined surfaces will not be affected. Based on the literature survey, it was observed that little attention was paid to the variant when the axis of symmetry of the punch is kept perpendicular to the formed surface of the blank throughout the forming process. Thus, a set of experimental determinations was carried out, in order to determine the influence of process parameters on the dimensional and shape accuracy of formed parts.

A final step of the research was the analysis of the energy consumption during the single-point incremental forming process. This energy analysis is based on the measurement of the electric power consumed by the electric motors in each kinematic joint. Acquiring the power in the robot joints made possible the analysis of the degree of load for each kinematic joint, respectively for each electric motor. The evolution of the power was used to qualitatively validate the values of the torques in the kinematic joints determined by simulation. Finally, the influence of the position of the workpiece in the robot workspace on the values of the torques in the kinematic joint was studied. This analysis can be used further to optimise the energy consumption of machining processes.

GENERAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

1.1. General conclusions

The present work aimed to study the use of industrial robots in an incremental forming process, the influence of their use on the improvement of energy consumption in the machining process, as well as on the dimensional and shape accuracy of the parts, by reducing the dynamic resisting torque on the robotic structure.

Following the conclusions emerging from the analysis of the state of the art, research directions were chosen, and theoretical and experimental research was initiated.

In order to carry out the theoretical and experimental research by incremental forming process, a 0.67 mm thick of DC04 metal sheet was chosen. The shape of the formed parts was a truncated cone type in which three representative geometrical and process parameters were varied: the wall angle, the incremental step and the type of trajectory used. Four types of trajectories were used to generate the shape of the parts: circular and spiral, with fixed axis and tilted axis variants for each of them.

Several specific software packages were used for the theoretical and experimental research:

- Bluehill 2 for processing and interpreting the results obtained from the uniaxial tensile test;
- SprutCAM for generating commands for the movement of the punch along the paths that are necessary to obtain the final shape of the part (code for controlling robot movements);
- ANSYS LS-DYNA for numerical FEM analysis of the incremental forming process;
- Catman for acquiring and analysing the values of the three components (Fx, Fy, Fz) of the forming force;
- GOM Correlate for visualisation and evaluation of the data from deformation measuring performed with the ARAMIS optical system;
- GOM Inspect for visualisation and evaluation of data obtained from measurements with the optical 3D measurement system - ATOS Core;
- MATLAB - Simulink for making and simulating the kinematic and dynamic models of the KUKA KR 210-2 robot.

The theoretical and experimental research carried throughout the work allowed the following conclusions to be drawn:

- from the point of view of the technological equipment used for a flexible configuration that meets the requirements of the industrial environment in terms of time, performance and production costs, in the case of the incremental forming process, a good compromise could be the use of industrial robots;
- the forces developed during incremental forming processes is a subject of major interest in research, because of their influence on process limitations (especially in terms of the accuracy of machined parts), and their values have a direct effect on energy consumption during the forming process;
- due to the possibility of vertically positioning the sheet metal that needs to be processed by incremental forming with industrial robots, the deformation behaviour of the parts can be evaluated online, by measuring the deformations of the processed material during processing, by means of an optical measuring system;
- experimentally obtained results of the values and distributions of the major strain ε_1, minor strain ε_2, Von Mises equivalent strain ε_{VM}, and thickness reduction were similar to those obtained by numerical FEM simulation, which led to the validation of the developed FEM analysis model;
- after comparing the experimental results with the theoretical ones (resulting from the numerical simulation) of the variation of forming forces, both in terms of time evolution and of the maximum and minimum values obtained, a good correspondence was observed;
- after comparing the two types of trajectories, with fixed axis and with inclined axis of the end effector (punch), it is noted that the processing with trajectories with fixed axis, keeping the axis of the punch perpendicular to the initial plane of the blank, leads to an even distribution in terms of strain and thickness reduction;
- based on the analysis of the results obtained from the experimental determinations, from the point of view of dimensional and geometrical (shape) accuracy, the forming strategy with trajectories having the axis of the punch oriented perpendicular to the forming surface of the blank (inclined axis), allows obtaining parts with a real profile closer to the theoretical profile, being superior to trajectories with fixed axis;
- the measurement results validated the hypothesis that forming using inclined axis trajectories represents the best compromise between maximum value and even distribution of strain and thickness reduction;

- decreasing the incremental step of the punch leads to values closer to the standard profile in terms of level difference at the bottom of the part;
- from the point of view of the forming force, it was observed that a significant influence on it, after the three directions, in the incremental forming process, is the forming strategy (in terms of the trajectories used), followed by the incremental step and the wall angle;
- the development of the dynamic model of the KUKA KR 210-2 robot has led to the possibility of determining the resistance torques of the kinematic joints of the robot during the incremental forming process;
- the analysis of energy consumption during the single-point incremental forming process was carried out qualitatively, based on the comparison of the evolution of the currents in relation to the torques in the kinematic joint calculated by simulation;
- it was observed that the variation in time of the differential torques in the joints and the currents consumed in the kinematic joint has a similar evolution, qualitatively speaking;
- with regard to the position of the metal sheet in the robot workspace (repositioning, reorientation of the metal sheet according to the robot base, and change in the trajectories to be taken by the punch in order to produce a part), both the resistive torques and the currents become smaller as the distance between the metal sheet and the robot decreases;
- the minimum value of the distance between the robot and the part is given by the functional limits of the forming system;
- it was not possible to perform a quantitative analysis to validate the calculated values of the torques in the kinematic joint based on the measured currents, given the unknown values of the moments of inertia of the structural connecting elements (robot arms) and the robot compliance, which are extremely difficult to be determined during the robot operating phase;
- the developed and validated model allows the user to evaluate the influence of the position of the workpiece on the values of the torques in the kinematic joint;
- by integrating the trajectories obtained based on the CAM model, and the forming forces, obtained based of the CAE model, into the MATLAB/Simulink-Simscape model of the robotic structure, the user will be able to calculate/control the movement of the robotic structure, in direct and inverse kinematics, as well as the dynamic stresses on it.

1.2. Personal contributions

Throughout this PhD thesis, a number of contributions was made to the study regarding the use of industrial robots in plastic forming processes, the most significant of which are listed below.

In terms of theoretical research:

- an experimental stand has been designed and developed, allowing the use of the industrial robot in the incremental forming process;
- data acquisition systems and computer-aided image acquisition and processing systems have been adapted, calibrated and implemented for the studied process;
- programs for the acquisition, filtering and processing of experimental data have been developed;
- in order to determine the mechanical characteristics, the elastic-plastic behaviour of the material used (DC04 steel) was determined by uniaxial tensile test;
- truncated cone shaped parts were produced, using various geometrical and process parameters;
- the values and distributions of strain and of thickness reduction of the metal sheet were experimentally determined;
- the results obtained validated the finite element model developed;
- the influence of some input, geometric and process parameters on the quantities characterising the behaviour in incremental forming was determined;
- the influence of the variation mode of forming forces on the final accuracy of the part for various trajectories and technological parameters was determined;
- the dimensional and shape accuracy of the formed parts was evaluated, the results obtained indicating that the machining strategy with trajectories having the axis of the punch oriented perpendicular to the surface of the part wall (inclined axis) allows obtaining parts with a real profile closer to the theoretical profile, being superior to trajectories with fixed axis;
- a methodology for the analysis of energy consumption during the single-point incremental forming process has been proposed and validated, allowing the user to evaluate the influence of the position of the workpiece in the robot workspace on the values of the torques in the kinematic joint;
- research has been carried out on the influence of the relative position of the metal sheet with respect to the machining system on energy consumption, and it has been noted that

both the resistive torques and the currents become smaller as the distance between the workpiece and the robot decreases.

1.3. Future research directions

Considering the results obtained in this PhD thesis, there is certainly scope for further research in the following directions:

- evaluation of surface quality (roughness) of formed parts;
- making complex shaped parts with trajectories having the axis of symmetry of the punch oriented perpendicular to the surface of the part wall (inclined axis);
- development of CAM software programs that take into account the specific features of incremental forming process;
- performing a quantitative analysis to validate the calculated values of the torques in the kinematic joint based on the measured currents.

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