Incremental forming using KUKA KR210-2 industrial robot - research regarding design rules and process modelling

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Abstract. Incremental sheet forming (ISF) process show a great potential in the manufacturing of small series production or prototype development parts. One of the sheet metal forming process, where the contact between punch and metal sheet is in a single point, is known as single point incremental forming (SPIF). The part is manufacture with a simple tool, known as punch, that performs a series of combined movements on the vertically and horizontally directions. The paper introduces a study regarding the design rules and process modelling of this unconventional process, by means of a KUKA KR210-2 industrial robot as technological equipment able to control the correlated movement of the punch. Supplementary, the design of the experimental layout, the process simulations and the singularity problems are considered.

1 Introduction

Process flexibility is a critical design consideration in complex product supply chains facing an uncertain demand. The modern manufacturing processes have known in the last 25 years an increased improvement in the name of flexibility configuration, which not only show a great potential for the creation of unique parts, commonly known as rapid manufacturing methodologies, but also improved existing technologies like computer numerical control (CNC) systems.

Within the manufacturing processes of the sheet metal forming, using a conventional forming process means expensive dies, complicated forming tools and less flexibility. The challenge was to find a cost-effective flexible configuration that could meet industry demands regarding changing requirements in a timely and cost-effective manner. Thereby, ISF process has gained a continuous growing interest, among classical sheet metal forming processes, mainly on the small batch sheet or rapid prototyping parts. Due to the advantages that it offers in analogy with traditional sheet metal forming processes, in terms of lower production cost and shorter manufacturing time of the parts, mainly due to the fact that the forming process is achieved through a simple and relatively inexpensive universal tool [1], known as the punch, it can be stated that ISF process allow a high degree of flexibility.

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2 SPIF process

Of all the technological versions of this process that have emerged over time, the most used is SPIF process. The automotive, the aircraft, the aerospace, and the medical implants industries, wherever small series or unique parts are necessary, represent the main applications of SPIF process [2-5].

Below, in figure 1, is presented the principle of the SPIF process. The process components are very simple ones, namely a hemispherical punch (1), the sheet metal (2) and the fixture system (3). There will be a series of combined movements that the punch will execute, mostly continuous movement in XY plane, followed by a vertical movement along Z-axis. The remarkable thing about it is that there is no need for high-cost dedicated tools or dies.

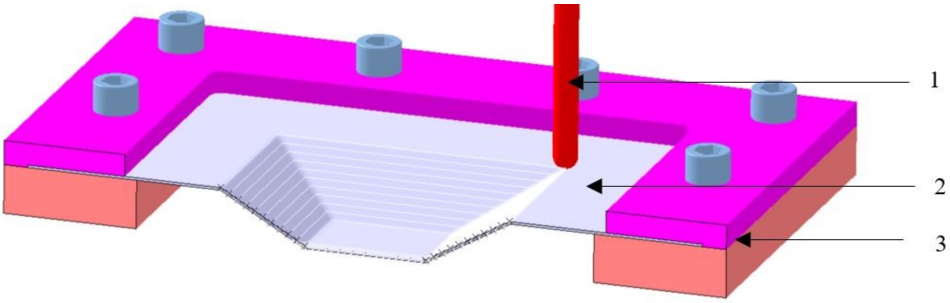


Fig. 1. SPIF process principle.

While not requiring expensive technical equipment, SPIF process is relatively slower, in analogy to conventional metal forming processes. Currently, there is no specific type of technological equipment that is widely accepted for the SPIF process, given that this process is relatively new. The literature mentions the use of four types of technological equipment, namely: articulated industrial robots [6], parallel robotic structures [7], CNC milling machines [8] or specially designed forming machines [9].

With the use of the same equipment, due to the great flexibility of the process, there are many manufacturing possibilities of the different shapes and sizes of parts. However, the complexity of the geometric shapes that can be formed depends on many process parameters [10-12], such sheet thickness, forming angle, tool size, step size, punch toolpath or the available power of the technical equipment.

With the development of computer numerical control, the punch toolpath generation become a key topic linked to the SPIF process, especially in terms of part conformity and productivity. Until recently, most research has focused on sheet metal formability using standard CAM milling toolpaths [10-11]. However, regardless of the parameter studied, the most used tool trajectories were Z-level contouring and spiral toolpaths.

If we relate to the technical equipment, the major research in this area has been done on 3-axis CNC milling machines, where the metal sheet in formed only on three directions, due to the less degree of freedom (DOF) compared with 5-axis CNC machines or industrial robots. Compared with other types of equipment, the 3-axis CNC milling machines are used in large number on SPIF [13-16]. The major drawback of this equipment is given by the limitation of the working area. Despite that CNC machine market is constantly evolving, when complex shape geometries are required, the industrial robots represent a very good alternative to 3-axis CNC machines, ensuring a high degree of flexibility due to their large workspace and advanced kinematic. The limitation of lower stiffness and accuracy for robotic structures can be eliminated by parallel robotic structures. Also, the industrial robots proved to be effective in forming a part with the same standard parameters, because require lower values of the forming forces, compared to CNC milling machines [17].

In this paper is presented a study regarding the design rules and process modelling of this unconventional process, by means of a KUKA KR210-2 industrial robot as technological equipment able to control the correlated movement of the punch.

3 Robot-based incremental sheet forming – process modelling and design rules

Due to lack of optimization for industrial implementation in the forming process of the robot-based incremental sheet, it is required a proper design and process modelling from the early stages of the project in order to the industrial robot to benefit from high travel speeds and flexibility compared to the values obtained as a result of using a CNC milling machine [10-11].

Is known that advantages offered by robot structure, in terms of high travel speeds and flexibility, lead to lower value of the forming forces or less energy consumption, when compared with CNC milling machines [18 - 20]. A comparison, at simulation stage, was made between CNC milling machine-tool and an industrial robot by Breaz et. al. [21]. Using simple toolpaths showed no significant differences between industrial robots and 3-axis CNC machines. But the overall processing time the amount of processing time reduction was around 33% when the industrial robot used all of its kinematic capabilities.

In the following lines will be presented the steps taken during the SPIF process where the parts were manufactured with the 6 DOF of the anthropomorphic robot.

3.1 Experimental configuration

In order to demonstrate the use of robots as technological equipment in the SPIF process, mainly in terms of design rules and process modelling, it was chosen the KUKA KR 210-2 2000 industrial robot as an alternate option to a CNC milling machine.

Considering that the study of the process parameters will be followed, one of the great advantages offered by the robot is represented by the vertical positioning of the part. Thus, as against the case of using a CNC milling machine, where the part it is positioned horizontally, so the data regarding the strain and thickness reduction can be determined only at the end of the process, in case of using an industrial robot, an optical measurement system can be mounted behind the part, offering the possibility of determining in real time the value and the distribution of mentioned parameters.

First step was represented by design of a proper metal sheet fastening system. The fastening system (fig. 2) consist of a frame attached to the floor through four chemical anchors, on which the vertically positioned mental sheet fixing frame is attached. The metal blank is rigidly fastened between the clamping frame and support frame by means of 12 screws.

After designing the fastening system, to determine if the technical equipment and optimal parameters used in SPIF are adequate, an important step is to determine the magnitude of the forming forces. Thus, ahead experimental research, a custom-made tool-holder working unit was developed [22].

The tool-holder working unit, presented in figure 3, offer a suitable punch fastening system that consist in a reconfigured ISO30 ER32 milling tool-holder, which is attached to the last element of the KUKA KR210-2 robot. Using this punch fastening system, tools with different sizes can be change easily and very quickly during the experiments.

A 3-component charge output transducer (PCB 261A13) it was mounted between the last element of the robot and the punch fastening system to be able to determine the size of the forming forces.

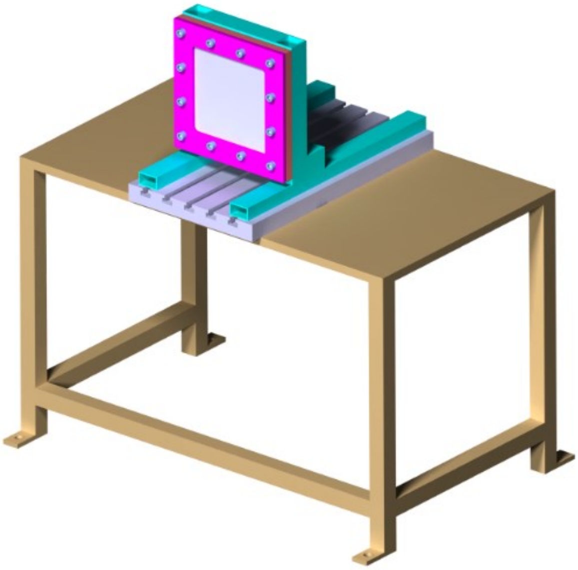


Fig. 2. The design of the fastening system.

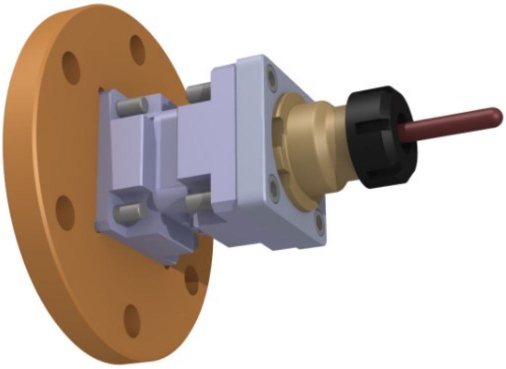
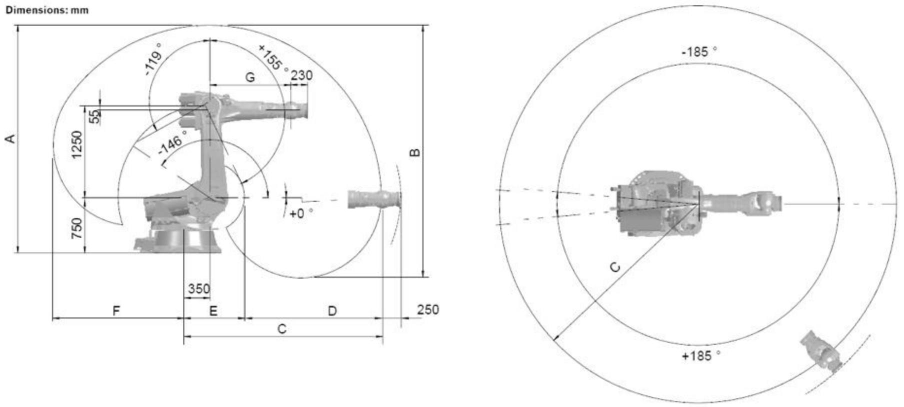


Fig. 3. The design of the tool-holder working unit.

Moving forward, the industrial robot, KUKA KR 210-2 2000 stands out through the high force and power, great flexibility, and high-speed movement, being a great option for performing continuous-patch and point-to-point tasks. The high-speed offered by the robot can surpass the SPIF drawback, the process being relatively slower, but further research must made.

The maximum working volume of this robot is 55 m^3, as can be seen in figure 4. The payload and the dead weight of the articulated components are statically compensated to a large extent by a closed counterbalancing system, which assists axis 2. Axes 1 to 3 are the main axes, axes 4 to 6 the wrist axes.

The most important KUKA KR210-2 characteristics are presented in table 1.



A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]	Volume [m^3]
3100	3450	2700	1875	825	1788	1100	55

Fig. 4. Overall dimensions of KUKA KR 210-2 2000 [23].

Table 1. KUKA KR 210-2 2000 characteristics.

Robot type	**KUKA KR 210-2**	
Number of axes	6	
Repeatability	±0.06 mm	
Rated payload	210 kg	
Max. total distributed load	610 kg	
Weight	1267 kg	
Working envelope	55 m^3	
Axis data	**Range of motion**	**Joint speed with rated payload**
Axis 1 (A1)	±185°	86 °/s
Axis 2 (A2)	+0° to −146°	84 °/s
Axis 3 (A3)	+155° to −119°	84 °/s
Axis 4 (A4)	±350°	100 °/s
Axis 5 (A5)	±125°	110 °/s
Axis 6 (A6)	±350°	184 °/s

Due to ongoing development of robotic controllers and CAD/CAM software solutions, the industrial robots can be considered as a very suitable technological choice to process operations where continuous path control is essential [24].

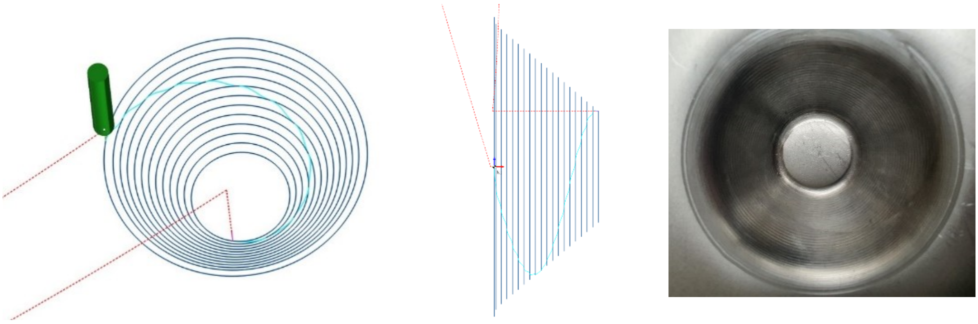
The "waterline/level" curves were used as processing trajectories, as shown in figure 5.a and 5.b. The curves were obtained by cross sectioning the 3D model of the cone frustrum by equidistant parallel planes, on Z-axes. The distance between these planes, on Z-axes is in fact the vertical increment of the process. By the approach, the processing trajectories (toolpaths) are in fact circles. The main advantage of using simple circular toolpaths is related to the ease of generating the code for commanding the end-effector of the robot to follow them, combined with the fact that simple toolpaths do not lead the robotic structure into singularity points. Of course, there are also drawbacks, related to the fact that these toolpaths are discontinuous ones (the tool has to be moved on the next circle each time the previous one is completed). During these lead-ins and lead-out movements, the contact with the workpiece is interrupted and moreover, lead-ins and lead-outs will create stress concentrators which could favour the occurrence of cracks. Also, discontinuous toolpaths will also influence the roughness of the processes surface, by increasing it.

Continuous toolpaths, such as 3D spirals, which do not involve lead-in and lead-out movements could be a better choice, with regards of plasticity and roughness of the part, but are also much more difficult to be generated and are much more problematic with regards of avoiding singularity points.

The software selected to build the kinematic models and run the necessary simulations was the SprutCAM Robot. The kinematic model of the robot was build based on the 3D model provided by KUKA, using a specific template from SprutCAM. The punch trajectories were then created as cutter location data files, based on the previous CAD 3D model and the robot kinematics. Among them, problems related to the limits of the robot working space and singularities was identified and solved.

The geometry of a truncated cone is displayed in figure 5.c as a result of the studies that were carried out.

The experimental layout consisting of the designed fastening system, the KUKA KR 210-2 robot and the designed tool-holder working unit is presented in figure 6.



a) b) c)

Fig. 5. a) Proposed truncated cone geometry; b) “Waterline/level” curves; c) The manufactured part.

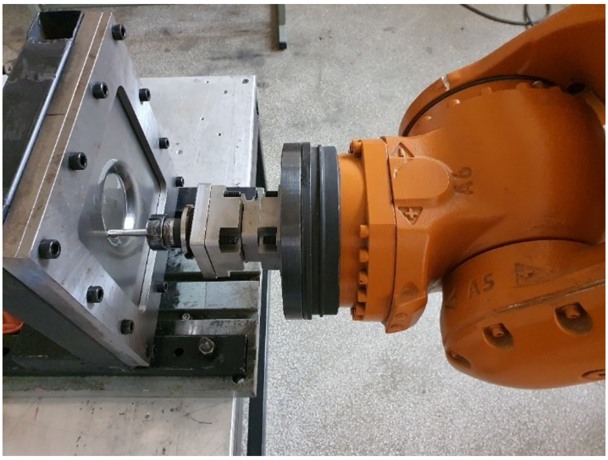


Fig. 6. Experimental layout used for SPIF by means of KUKA KR210-2 robot (detail).

4 Conclusions

Despite that CNC machine market is constantly evolving, the serial industrial robots represent a very good alternative that could meet the SPIF process demands regarding changing requirements in a timely and cost-effective manner. Considering the limitations of the robot forming process in terms of optimization and industry implementation, a proper design and process modelling must be developed from early stages of the project.

Using SprutCAM software, problems related to the limits of the robot working space and singularities was identified and solved. Upon simulation, the robot was controlled by the program code which was generated based on the robotic structure's kinematics and the 3D model of the desired part.

The study shown that using a proper designed metal sheet fastening system, together with a custom-made punch-fixer attached to KUKA KR 210-2 robot, resulted in a successfully executed truncated cone shape. Also, the fastening system offers the opportunity to mount an optical measurement system to determining in real time the value of the distribution of strain and thickness reduction, while tool-holder unit include a force transducer with which it can be determined the magnitude of the forming forces.

Further research will test the influence of the process parameters towards part accuracy, the consequences of the punch being constantly perpendicular to the processed surfaces, the study of the forming forces and the energy consumption.

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