Tool-holder working unit used for robot-based incremental sheet forming

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Abstract. The diversity of industrial robot applications is constantly growing, and their use in manufacturing processes is increasing year by year. One of the most flexible sheet metal forming process, used mainly for rapid prototyping or small series production, is represented by the single point incremental forming (SPIF). Usually, incremental sheet forming processes are performed by means of CNC milling machines or industrial robots, both having advantages and disadvantages. Due to the superior number of axes, especially when compared with 3-axis CNC milling machines, one of the most obvious advantage of the industrial robots rely upon their superior kinematic. The approach of this paper tackles the problem of designing a tool-holder working unit for SPIF process performed through a KUKA KR 210-2 industrial robot. After designing of the working unit, and simulating the tool path, the generated program code was used afterwards to successfully control the robot to obtain a truncated cone-shape part.

1. Introduction
In an obvious global competition, industry requirements suggest the use of small series and large variety production. Due to their need to develop very complicated forming tools, conventional sheet metal forming processes, like deep drawing or stamping, are not able to meet the growing demand for shortening product development cycles. Recently, SPIF process has attracted a continuous growing interest in the manufacturing of prototype parts or small series production due to the customer demand custom products [1-3].

Compared with conventional sheet metal forming processes, the SPIF process present some unique advantages, such as low cost of tools, increased formability, and process flexibility. SPIF is a forming process where a sheet metal is incrementally formed into a designed shaped, usually, by a round tipped tool, controlled by a CNC machine or an industrial robot, that moves along a designated tool path.

This paper describes the steps taken for development of a proper tool-holder working unit for SPIF process performed through a KUKA KR 210-2 industrial robot.

2. Single point incremental forming
The sheet incremental forming process is one of the most flexible metal forming processes. This relatively new process is used in the forming of sheet metal part, resulting in the production of small series or prototypes metal parts, and beyond rapid prototyping and unique parts.

Figure 1 present the principle of the SPIF process, where the metal sheet (2) is fixed between a retaining frame (3) and a support plate (1). With no need for high-cost dedicated dies or tooling, based
on a simple hemispherical punch, noted with (4), that executes a series of combined movements following a predefined path, the metal sheet is incrementally formed into its final shape.

Figure 1. The principle of the SPIF manufacturing process.

In contrast with conventional metal forming processes, the SPIF process is relatively slower, but at the same time does not require an expensive technical equipment. The available power of the technical equipment used, the speed of the punch and the length of the tool-path necessary to achieve the desired profile are directly linked to the manufacturing time of the parts. With such a great process flexibility, various shapes and sizes of parts can be manufactured with the same equipment.

Given the fact that the incremental forming process has a high degree of novelty, it is not possible at this time to discuss a certain type of technological equipment dedicated to this process and to be widely accepted. Thus, it was found mainly four approaches to the technological equipment used for processing by the incremental deformation process: specialized forming machines [4], CNC milling machines [3], parallel robotic structures [5] or articulated industrial robots [6].

The high flexibility and high travel speeds of the robots are favorable in the incremental forming process to produce parts at a lower deformation force than one obtained with the CNC milling machine [7-9]. Therefore, industrial robots consume less energy compared to CNC milling machine and make the incremental forming process economical. However, the robot forming process has not yet fully optimized and implemented in industry. But with major automotive companies, such as Ford, interested in the SPIF technology, and in order to develop the process for industry adaptation, different studies regarding the usage of industrial robots can be found [1, 10].

With multi-parameters that are affecting the process, to validate the complex methodology for system design and prototyping, Callegari et al. [11] performed several experiments. It was concluded that most the important parameters are number of axes of the task, the size and the toolpath of the punch, types of materials, the kind of interpolation between the points. Ismail et al. [12] conducted experimentally investigation of robot based SPIF on AA3003 aluminum alloy sheet. Using Taguchi orthogonal array and ANOVA is was showed that a better surface roughness of the part can be achieved at 150 mm/s of robot speed, with a 0.3 mm of step size and 45 degree of wall angle. Ingarao et al. [13] reports an analysis of energy consumption, including a study of the power of single-point incremental forming processes, developed on a 6-axis robot. By analyzing the production mode time share and the energy demand for four different parameter combinations, it was concluded that the forming time is the most dominant factor in the energy demand of SPIF processes. Belchior et al. [14] studied the ability of Fanuc S420iF industrial serial robot to form a part with SPIF process. The tool center point pose errors are calculated with the elasto-geometrical model and the corrected tool path is generated. Based on this elastic model of the robot and the force prediction, the experimental result showed a difference of 1 mm between the final shape made by milling machine and the one made by the robot.

In all research studies presented so far, researchers mention the presence of forces on three directions during SPIF process. Knowledge about the size of the deformation force and the deformations distribution in the incremental forming process is very important, especially in
determining the adequate equipment and optimal parameters in the process for sheet forming. A preliminary step before determining the magnitude of forces and hence if the technical equipment is suitable for incremental forming process, is to use a proper tool-holder working unit for robot-forming.

3. Tool-holder working unit for robot-based incremental sheet forming

Designing a proper tool-holder working unit for SPIF process represents an important step ahead experimental research. Given that punches with different sizes are usually used for incremental forming study, to be able to change them very quickly during the tests and to ensure their secure fixation, a suitable punch fastening system must be designed.

The experimental layout, presented in figure 2, used for SPIF consists of the KUKA robotic system (1), the tool-holder working unit assembly for fixing the punch (2), the punch (3) and the fastening system (4).

![Figure 2. Experimental layout.](image)

The tool-holder working unit assembly is made of a connecting flange attached to the last element of the robotic arm, a force sensor, a tool-holder, and a punch. The assembly was fastened with four socket countersunk head screws UNF 1936 series ASME B18.3 3/8-24 x 1 Inch ft.

The connecting flange allows the link between the last element of the robotic arm and the force sensor. The force sensor is a 3-component charge output force sensor, model 261A13, made by PCB Piezotronics.

The punch tool-holder unit was designed starting from a milling arbor chuck holder CNC tool. Thus, an ISO30 ER32 tool-holder for ER32 collets has been reconfigured to be used for the incremental forming with the robot. An ER-32 collet chuck with an inside diameter of 10 mm was used to ensure the secure fixing of the punch in the tool-holder.

The tool-holder and the force sensor are fastened through a square flange. The link between the square flange and the sensor was made with four socket countersunk head screws UNF 1936 series ASME B18.3 3/8-24 x 1 Inch ft.

The sheet fastening system has been designed and produced for orientation and fixing the metal sheet, with assuring their free deformation during the forming process. The fastening system consist of a retaining frame fixed on support frame, a support plate, and a metal sheet. To improve the geometrical accuracy of the parts produced by SPIF, Popp et al. [15] proposed the used of a pressurize fluid under as a support die instead of the fixed backing plate. Even if the simulation results showed that the profile obtained was closer to the theoretical profile, further research must made to validate the proposed model.
4. The robot-forming system

4.1. The used equipment

The custom layout used for SPIF study consists of a KUKA KR 210-2 2000 industrial robot, a custom fastening system, a custom tool-holder unit, and a punch. The overall dimension for the KR 210-2 2000 robot are presented in figure 3 and table 1.

To simulate the trajectory of the punch for experiments, a 3D model of the desired part was designed in CATIA V5. Due to the development of CAD/CAM software solutions, as well as the capability of robotic controllers, processing operations that require continuous path control can now be performed with the help of industrial robots. Thereby, the commercial SprutCAM software program, was used to simulate machining process. SprutCAM includes a module for robotic processing, where the trajectories of the robot's final effector are generated as well as cutter location data files, based on the 3D model of the formed part and the kinematics of the robotic structure. Specific robotic process problems related to the singularities, collisions and/or reach limitation are checked and solved through this module.

![Overall dimensions and workspace of KUKA KR 210-2 2000](image)

**Figure 3.** Overall dimensions and workspace of KUKA KR 210-2 2000 [16].

**Table 1.** Dimensions of KUKA KR 210-2 2000 industrial robot [16].

| A   | B   | C   | D   | E   | F   | G   | Volume |
|-----|-----|-----|-----|-----|-----|-----|--------|
| mm  | mm  | mm  | mm  | mm  | mm  | mm  | m³     |
| 3100| 3450| 2700| 1875| 825 | 1788| 1100| 55     |

4.2. The part geometry and working parameters

A truncated cone-shape whose geometry is presented in figure 4.a was chosen to perform the experimental study. As conceptually illustrated in figure 4.b, the used contouring trajectory needed to shape the truncated cone-shape was a spiral tool path. The metal sheet is made from DC04 non-alloy steel, with very good deformability properties.

Table 2 include the geometrical data for this experiment. By using these working parameters, it was possible to obtain the truncated cone-shape without failure occurrence, as can see in figure 5.
Figure 4. Truncated cone-shape: a) dimensions, b) circular toolpath.

Table 2. Geometrical data of SPIF process.

| Geometrical data                  | Dimensions  |
|-----------------------------------|-------------|
| Metal sheet size                  | 250 x 250 [mm] |
| Metal sheet thickness             | 0.6 [mm]    |
| Punch diameter                    | 8 [mm]      |
| Vertical step size                | 0.5 [mm]    |
| Height of the truncated cone-shape| 40 [mm]     |
| Wall-angle of the part            | 60 [°]      |

Figure 5. Obtained part.
5. Conclusions
The first part of the paper presents the SPIF process, as well as the technical equipment on which the metal sheet can be successfully incrementally formed. The use of the KUKA KR 210-2 industrial robot as an alternative to CNC machines can meet the SPIF process requirements.

The second part of the paper presents a newly developed tool-holder working unit for SPIF process, as well as the fastening system, which increases the flexibility of the SPIF process.

SprutCAM, a commercially available CAM software package, was used for building the kinematic models and running the simulation. Finally, a truncated cone shape made from DC04 non-alloy steel was successfully formed.

Further research will be performed on three main directions:
- the influence of process parameters on the part accuracy;
- study of the forces within the SPIF process;
- the effect of keeping the tool always perpendicular to the processed surfaces.

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