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# A dynamic programming approach for minimizing the number of drawing stages and heat treatments in cylindrical shell multistage deep drawing

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ABSTRACT

Deep drawing is an important sheet metal forming process that appears in many industrial fields. It involves pressing a blank sheet against a hollow cavity that takes the form of the desired product. Due to limitations related to the properties of the blank sheet material, several drawing stages may be needed before the required shape and dimensions of the final product can be obtained. Heat treatment may also be needed during the process in order to restore the formability of the material so that failure is avoided. In this paper, the problem of minimizing the number of drawing stages and heat treatments needed for the multistage deep drawing of cylindrical shells is addressed. This problem is directly related to minimizing manufacturing costs and lead time. It is required to determine the post-drawing shell diameters along with whether heat treatment is to be conducted after each drawing stage such that the aforementioned objectives are achieved and failure is avoided. Conventional computer-aided process planning (CAPP) rules are used to define the search space for a dynamic programming (DP) approach in which both the post-drawing shell diameter and material condition are used to define the states in the problem. By discretizing the range of feasible shell diameters starting from the initial blank diameter down to the final shell diameter, the feasible transitions from state to another is represented by a directed graph, based upon which the DP functional equation is easily defined. The DP generates a set of feasible optimized process plans that are then verified by carrying out finite element analysis in which the deformation severity and the resulting strains and thickness variations are investigated. Two case studies are presented to demonstrate the effectiveness of the developed approach. The results suggest that the proposed approach is a valuable, reliable and quick computer aided process planning approach to this complicated problem.


## 1. Introduction

In today's highly competitive marketplace, it becomes crucial for manufacturing enterprises to appropriately design process plans that enable them to quickly respond to market demand. Designing process plans involves the selection of appropriate manufacturing steps and parameters that guarantee a successful product meeting the required specifications and quality level. This paper attempts to penetrate into the process planning function of the multistage deep drawing process, utilizing its technical models, to develop an approach that takes into consideration the objective of minimizing the number of drawing stages and heat treatments. Such an objective is directly related to maximizing throughput and minimizing manufacturing investment and running costs.

Deep drawing is one of the most essential processes in sheet metal forming. It is widely used in many industrial fields such as automotive and packing industries. In deep drawing, a blank sheet is drawn in a hollow cavity (die) using a normal force applied by a punch to produce a hollow shell. Meanwhile, a blank holder is used to control and guide the flow of the blank material through applying a pressure parallel to the punch force. In many cases, the desired final dimensions of the hollow shell cannot be obtained in a single pass; for otherwise, undesirable deformation or failure will occur. In order to avoid that, redrawing of hollow shells is conducted along with heat treatment whenever necessary. Heat treatment is an annealing process that takes place at certain temperature and for a specific period of time depending on the materials being annealed. This process relieves any internal stresses and restores the ductility of the material, allowing for further redrawings.

Generally, the process design of manufacturing operations involves the determination of suitable process parameters that ensure the success of the process in producing the final product with the required specifications. In multistage deep drawing, the process parameters include the dimensions of both the punch

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and the die, the shape and dimensions of the blank, and the blank holder pressure vales for each stage in the process. Traditionally, the process design for deep drawing is conducted using rules-of-thumb and expert's judgment. As indicated by Huh and Kim (2001), this practice has been commonly followed in sheet metal forming until the 1990s when modern optimization theory and finite element methods were employed.

In the literature of multistage deep drawing, several recent papers utilized finite element modeling and simulation to guide the selection of the process parameters. Min, Jeon, Kim, and Kim (1995) used rigid-plastic finite element method to analyze the multistage deep drawing of circular cups. They studied the effect of changing the blank size, the corner radii of the tools and the clearances on reducing the forming loads. Zimniak (2000) studied the deep-drawing process of the multi-operational forming of a compressor cover. He demonstrated the benefit of using finite element simulation to select a suitable tool design from different designs to determine the optimum thickness changes in the final product.

Kim, Kim, and Huh (2001a) used finite element simulation to identify an unfavorable contact condition between the blank and the die in rectangular cup drawing with large aspect ratio. They proposed a design modification for the tool shape to improve the quality of the final product. A similar investigation was conducted by Ku, Ha, Song, Kang, and Hwang (2002) for the multistage deep drawing of a rectangular cup with extreme aspect ratio. Kim, Kim, and Huh (2001b) used an inverse finite element approach to determine the optimum blank shape and the intermediate die shapes for multistage deep drawing of elliptical and rectangular cups with large aspect ratio. Park, Ku, Kang, and Hwang (2004) carried out finite element analysis to select an optimized blank shape that minimizes the amount of removed material after the trimming process for multistage deep drawing of rectangular cups with extreme aspect ratio. Faraji, Mashhadi, and Hashemi (2010) used finite element simulation to improve the process parameters for multistage cylindrical shell deep drawing with the objective of maximizing the ratio between the initial blank diameter and the final shell diameter. In a case study, they were able to reach a value of 9 for that ratio.

Some research work was concerned with process planning and improvement for the multistage deep drawing of a specific blank material. Mori, Murao, and Harada (2003) studied the multistage deep drawing process of long pure titanium cups. They showed the benefit of conducting electrochemical coating to produce an oxide surface layer that helps in preventing seizing. Kim and Hong (2007) studied a multistage deep drawing process of a circular cup from molybdenum sheet which is characterized by high mechanical strength at high, as well as low temperatures. They used a simulated annealing optimization approach concurrently with finite element simulation in order to find the safe working process parameters. Paćko, Dukat, Śleboda, and Hojny (2010) conducted experimental and finite element analysis for the multistage deep drawing of AA5754 Aluminum alloy to produce a rectangular cup. They showed that the proper conditions of friction on the tool-workpiece contact surface is crucial for the correctness of the finite element simulation, and the friction conditions can be improved both by applying suitable lubricant and properly selecting the areas of the workpiece to be lubricated.

In the process design of multistage deep drawing, it is necessary to minimize the number of drawing stages and heat treatments which directly leads to the minimization of manufacturing costs and lead time. Yet, as indicated by Wifi, Abdelmaguid, and El-Ghandour (2007), the research work that considered that objective is quite few. Cao, Li, Xia, and Tang (2001) developed an optimization approach based on suitable design rules and inverse finite element for constructing suitable die shapes for the first draw and subsequent drawing steps. The new approach is compared with another one that is based on industrial experience for a selected case from the automotive industry. The new approach was capable of reducing the number of drawing steps from 10 to 6 with lower maximum void volume fraction which is a measure of tearing potential; while the press loads are almost identical. Sonis, Reddy, and Lal (2003) asserted that there is a need for analytical tools that can guide process planners in determining the minimum number of drawing stages in multistage deep drawing processes. They developed an improved model for determining the limiting drawing ratio (LDR) which is defined as the ratio between the blank or shell diameter at the beginning of the stage and the shell diameter at the end of the stage. They demonstrated how this model can be used to reduce the number of drawing stages in two case studies. Ramírez, Packianather, Domingo, and Pham (2010) developed an evolutionary approach for optimizing the multistage forming process of Aluminum cups. Two objectives are considered: the minimization of total process time and the minimization of total process cost. Both objectives are directly related to the minimization of the number of drawing stages. However, they did not take into consideration the option of conducting heat treatment, and their model does not contain constraints that ensure the feasibility of the process plans.

This paper is the first attempt to provide a systematic process planning approach for the multistage deep drawing of cylindrical shells with the objective of minimizing the number of drawing stages and heat treatments. Based on conventional rules that define the safe working ranges for the process parameters, a dynamic programming (DP) approach is developed. The DP generates a set of optimized process plans that are validated using finite element analysis. The reset of this paper is organized as follows. In Section 2, the conventional CAPP rules that are used to define the working ranges for the main process parameters that have a direct effect on the search structure of the DP approach are presented. In Section 3, the developed DP approach is illustrated. A description of the validation approach conducted by finite element analysis is given in Section 4. In Section 5, two case studies are presented, and the conclusions are provided in Section 6.

## 2. CAPP rules for multistage deep drawing of cylindrical shells

The multistage deep drawing process of cylindrical shells is schematically illustrated in Fig. 1 showing its related parameters and their notations. The first step in designing the multistage deep drawing process of cylindrical shells is to calculate the initial blank diameter $d_0$ based on the final desired shell diameter $D$ and height $H$ along with other final shape parameters. The diameter of the resultant cylindrical shell after each stage of the multistage deep drawing process ($d_i, i > 0$) has to be selected such that no failure occurs. This can be done by keeping two constraints satisfied. The first constraint, as defined by Aida (1998) and Suchy (1998), is represented in the following simple form.

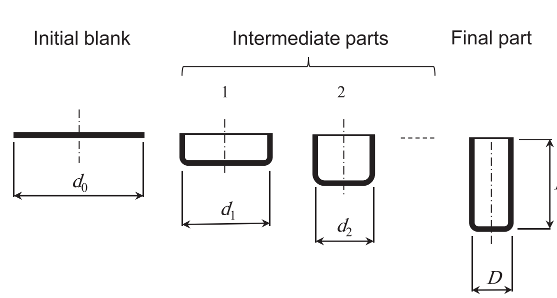

**Fig. 1.** Schematic diagram of the multistage deep drawing process.