

DEEP DRAWING IN METAL FORMING: A MACROMODELING PERSPECTIVE

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Abstract

Deep drawing stands as a prominent metal forming technique widely embraced by manufacturers for its efficiency and versatility. This process yields high-strength, lightweight components at a lower cost compared to alternative methods, making it a preferred choice across industries. Key advantages of deep drawing include swift press cycle times, reduced operations for finishing parts, and the capability to fabricate intricate geometries that are otherwise unattainable through conventional methods. As demand for complex parts with superior performance continues to rise, the significance of deep drawing in modern manufacturing landscapes becomes increasingly pronounced.

Keywords: Deep drawing, Metal forming, Manufacturing, Complex geometries, Cost-effectiveness

Introduction

Deep drawing is one of the most popular metals forming methods available to manufacturers. The deep drawn process produces high-strength, lightweight parts more cost-effectively than other methods. Among the advantages offered by deep draw are: rapid press cycle times, fewer operations required to finish a part, the ability to create complex geometries unattainable through other processes.

Today, forming simulations are mainly used in a trial-and-error scheme to develop a forming process which produces acceptable parts. With increasing of complexity and size of data in the finite element model, computational time also correspondingly increases. It must therefore be the objective to eventually develop an efficient automated optimization of the forming process.

The new tendencies in design, optimization and control of the metal forming process determined the need of using new modelling techniques (Herderich 1990, Hsu et al. (2000), Viswanathan et al. 2003, Bonte, 2005; Maier, 2010, 2011). The main characteristic of the new models is their very short response time, this being the reason why they can be used for real-time control of the process. By analogy with the finite element method the new developed modelling techniques are called metamodeling (Bonte, 2005), reduce order modelling (Maier, 2011) or macro-modelling of the deep drawing process. For example, Maier and col. (2011, 2010) present a new reduced order technique with the goal to develop such models. The idea of reduced order modeling is to use two models

for optimization: a fine model (finite element model) of the process which has high accuracy with computationally expensive to solve and a reduced order model associated with the adaptive space mapping, fast to solve but less accurate.

This work presents the macro-modelling method of the deep drawing process. The basic principle of the suggested technique consists of decomposing the process into macro-elements – elementary deep drawing process and their customization starting from the generalized elementary deep drawing process.

According to the proposed method, the deep drawing process of any part will be divided into macro-elements – elementary deep drawing process, each one representing a particular case of the generalized elementary deep drawing process, presented in figure 1.

1. Terms definition

The definitions of the terms used in this paper are:

- a) Deep drawing process**, considering his extended definition, include four constitutive elements:
 - i) blank, ii) tools, iii) final part, iv) sheet metal forming process. In this context, the deep drawing process is completely defined if the values of the specific parameters for all elements are give. The change of any specific parameter of a constitutive element determines another deep drawing process definition.
- b) Elementary deep drawing process** represents a part of the deep drawing process associated to a part of the blank that turns into a part of piece when a part of the tools generates a part of the process. An elementary deep drawing process is autonomous, can be independently realized and he has the same global specific parameters as the deep drawing process. The deep drawing process is equivalent to the simultaneous conduct of all its elementary process.
- c) Specific deep drawing process parameters** influence both how to conduct and outcome of the process. This is the reason why these parameters are used to specify an unique process. On the other hand the specific deep drawing process parameters refer to one from the four constitutive elements of the process. An elementary deep drawing process or whole the deep drawing process is completely defined by 22 specific parameters presented in the table 1. The specific parameters can be devided in two categories: *characteristics* and *descriptors*. In the same time, the specific deep drawing process parameters are two types: i) *global*, associated to whole deep drawing process and ii) *local*, associated to an elementary deep drawing process. The local specific parameter belonging to the whole process is an vector containing the values of this specific parameter corresponding to all its elementary process.
- d) Characteristics** are these specific parameters corresponding to the „materialized” part of the process represented by: i) blank, ii) tools, and iii) final part. The values of the characteristics sets before starting the

deep drawing process and remains constant during the process. In the table 1, the deep drawing process characteristics correspond to the lines 1-17.

- e) **Descriptors** are these specific parameters corresponding to the „phenomenological” part of the process, represented by his fourth constitutive element - sheet metal forming process. The descriptors define sheet behavior under the action of the tools during deep drawing process. They are represented both by the reaction forces and the specific defects, i.e. fracture or wrinkles due to sheet instability. Four important remarks the authors underline: *i)* descriptors values can be only measured during the process, not settled before; *ii)* the descriptors values evolving during the process; *iii)* descriptors values and its evolution during the deep drawing process distinguish between the different ways of sheet behaviour; *iv)* descriptors values and its evolution depend only on the characteristics values. The deep drawing process descriptors corresponds to the lines 18-22, table 1.
- f) **The contour line** represents the intersection between the part and different planes. It can be: *primary* if the intersection is done with the separation plane, *secondary* if the intersection is done with a plane perpendicular to the tangent to *primary contour line* in one of its points or *tertiary* if the intersection is done with a plane perpendicular to the tangent to *secondary contour line* in one of its points.
- g) **The macro-model of the deep drawing process** is equivalent to the ensemble of all its elementary process and represents the *sheet behavior model* during deep drawing process.

1. Macro-modelling Method

The macro-modelling method of deep drawing process is presented considering the principal aspects: the principles and the procedure of the method.

a) Principles of the macro modeling method

Real deep drawing process decomposition consists in: *i)* the *delimitation* of each elementary process and *ii)* his *identification* starting to a generalized elementary deep drawing process in order to establish her characteristics.

Delimitation of each elementary deep drawing process is based on the following-

Conditions:

- a delimited area of the blank must to determine a delimited area of the finished part after deep drawing process;
- in a delimited area, the value of characteristics remains constant and distinct from those corresponding to adjacent areas;
- at the separation zone between two adjacent areas the interaction must to be minimum.

Criteria: The delimitation of each elementary deep drawing process is based on the decomposition of the primary contour line CP in segments. The primary contour line is a closed contour and it is obtained by the intersection

between the finished part and the separation plane P (Figure 2). The delimitation of the segments is made considering that the maximum variation of each characteristics belong a segment are lower than a limit value.

The limit values are imposed by the designer of the process considering the imposed precision of the macromodeling process. As these values are smaller, the more complex is the model and more accurate is the modellisation.

Identification of each elementary deep drawing process consist in two steps:

- In the first step, the generalized elementary deep drawing process is customized considering the real deep drawing process. It results the value of the six global characteristics presented in the lines 1 – 6, table 1. They will play the role of constants for all models of the elementary deep drawing process. The global characteristics values are determined considering input data regarding sheet blank, tools and finished piece.
- At the second step the generalized elementary deep drawing proces is customized in order to perform the identification of each elementary deep drawing process. The identification for an elementary deep drawing process represents the determination of 11 local characteristics (table 1). They will play the role of constants for the model of the considered elementary deep drawing process. The identification is made during the delimitation of the elementaries deep drawing process: first, the value of local characteristics are evaluated in each point of the primary contour line CP in order to obtain her decomposition respecting the above criteria. The borders of a segment of the primary contour line determine the borders of the blank, finished piece and tools corresponding to the elementary deep drawing process. The average of the local characteristic values belong the segment represent the value of the local characteristic corresponding to the identified elementary deep drawing process.

b) Macromodelling procedure

The couple – delimitation, identification - represent the macro modeling procedure. They are made simultaneously and consist in the examination of the primary contour line CP in order to determine the value of five local characteristics, representing decomposition criterions - $R1_i$, $R2_i$, $r1_i$, $r2_i$, H_i , in each point A_i .

The piece intersects with a plane S_i , that contains the point A_i and is perpendicular to the primary contour line CP (and obviously to the separation plane P). It results the secondary contour line CS_i (Figure 3), which is an open contour, length - A_iB_i , where B_i is the point on the contour which is at the greatest distance from the plane P . The distance between the point B_i and plane P represents the value of the criterion H_i . Evaluating the curvature of the secondary contour line CS_i for different points of the segment A_iB_i , the points M_i and m_i are obtained, where the curvature has extreme values. In point M_i , is the maximum positive curvature (maximum convexity) and the contour curvature radius is $r1_i$. Similarly, in point m_i , the curvature is maximum negative (maximum concave) and the contour curvature radius is $r2_i$.

Then, as shown in Figure 4, the part surface intersects the plane $T1_i$, which passes through the point M_i and is perpendicular to the secondary contour line CS_i (and, obviously, to the plane S_i). The intersection line between the plane $T1_i$ and part surface is the tertiary contour line $CT1_i$ (Figure 5). The curvature radius of tertiary contour line $CT1_i$, in the point M_i is $R1_i$. Similarly, the plane intersects with the part surface $T2_i$, passing through point m_i is perpendicular to the secondary contour line CS_i (and, obviously, to the plane S_i). The intersection line between the plane $T2_i$ and the part surface is tertiary contour line $CT2_i$ (Figure 6). The curvature radius of tertiary contour line $CT2_i$ in point m_i is $R2_i$.

In point A_i on the primary contour CP , the 5 first values of the 6 decomposition criterions of the drawing operation: $R1_i$, $R2_i$, $r1_i$, $r2_i$, H_i were determined. To determine the value of the sixth criterion, the primary contour CP is covered, point by point, starting in A_1 , evaluating in each point the 5 first criteria. Considering it has reached the point A_i , the values of the five criterions corresponding to point A_i will be taken as reference. If on these points the values of all 5 criterions in relation to the reference will change, but the change is within the maximum allowed in a field, previously established, then all examined points belong to the same area.

When the variation domain is exceeded at least one of the five criterions, then that point, consider A_{i+1} , is limiting the current area and the values of the 5 criterions, corresponding to that point (A_{i+1}), are benchmark against which define the variation limits, which will be used to assess the following points of the primary contour CP . The current area is limited by the points A_i , A_{i+1} , B_{i+1} , B_i . The arc length $A_i A_{i+1}$ is L_i and represents the sixth value criterion from basic order number i . In this case n areas are bounded and elementary operations are identified, where actual drawing operation was decomposed. The n number of areas can be adjusted by corresponding modifying of variation permissible range, in which the 5 delimitation criterions must fall, for each area. If the variation allowable domain is smaller, the limited areas are more and smaller, the number of elementary process and models that form the sheet behavior model during deep drawing process is higher and the model accuracy, also.

1. Application of the Method

To illustrate how the real deep drawing process is decomposed in macro-elements, we consider the case of a rectangular box. As shown in Figure 7, the plastic deformation of the area $1-A0_1-A0_2-2$ of blank surface SM and the transformation of this area in $1-A_1-A_2-2$ of the final part PF are one of the elementary deep drawing processes that forms the real deep drawing process of the box, because, along the segment A_1-A_2 , the first 5 criterions values do not change. Due to symmetry, the symmetrical areas of the blank and final part are the subject of another elementary deep drawing process, same as above. On the other hand, the transformation of the area $2-A0_3-A0_4-3$ of blank surface SM in $2-A_3-A_4-3$ area of final part PF , and their symmetrical areas represent another elementary deep drawing process.

Adding to these the transformation of the area **2-A02-A03-2** of blank surface **SM** in the area **2A2-A3-2** of the final part, and three identical elementary deep drawing processes corresponding to the other corners of the box, it results the decomposition of deep drawing process in eight elementary deep drawing processes. Due to the symmetry, only 3 are distinct, others being identical with them.

Further, generalized elementary deep drawing process is customized for each of the eight elementary operations, thus obtaining values of the 11 local characteristics. Resulting is the data presented in Table 2.

1. Conclusions

The macro-modelling method determines a model of the real process having the advantages:

- a). reduce time-consumption for process and control system design;
- b). modelling the behavior of sheet metal during in the deep drawing process in order to optimize the process and assure good quality and consistency of the finished part;
- c). formal description of the sheet behavior during deep drawing process according to the presented method is achieved by building more simple models, on local level, continuously changing and adaptive, instead of a complicated global, unchanging model.
- d). control of deep drawing process when some descriptors are monitored. Any deviation of a descriptor value in relation to the reference value, as designed, beyond field of tolerance, then using the macromodel of deep drawing process, constructed according to the method, some of the features are changed, (change occurs in relation to the values set at design operation), so that all requirements of descriptors values to be satisfied.

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