Journal of Advanced Civil Engineering, Architecture, and Urban Planning
ISSN 3065-1425
Volume 11 Issue 3
July – September 2023
Impact Factor: 6.15
Enquiry: contact@continentalpub.online
Published by Continental Publication | https://continentalpub.online/index.php/jaceaup

MODELING METAL FORMING: MACROMODELLING INSIGHTS INTO DEEP DRAWING

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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 metal 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 metamodelling (Bonte, 2005), reduce order modelling (Maier, 2011) or macromodelling 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 macromodelling method of the deep drawing process. The basic principle of the suggested technique consists of decomposing the process into macroelements – 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 macroelements – 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 completly defined if the values of the specific parameters for all elements are gived. The change of any specific parameter of a constitutive element determine another deep drawing process definition.

b) Elementary deep draving 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 realised 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 behaviour 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 wrinckles due to sheet instability. Four important remarks the authors underline: *i)* descriptors values can be only measured during the process, not setted 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** represent 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 perpedicular to the tangent to *primary contour line* in one of its points or *tertiary* if the intersection is done with a plane perpedicular to the tangent to *secondary contour line* in one of its points.

g) **The macromodel 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. Macromodelling Method

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

a) Principles of the macromodeling 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 hers characteristics.

<u>*Delimitation*</u> 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 adiacent 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 obtined 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 represent 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 caracteristics 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 macromodeling procedure. They are maded simultaneusly and consist in the examination of the primary contour line CP in order to determine the value of five local characteristics, representing decomposition criterions - $\mathbf{R1_i}$, $\mathbf{R2_i}$, $\mathbf{r1_i}$, $\mathbf{r2_i}$, $\mathbf{H_i}$, in each point $\mathbf{A_i}$.

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

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

In point $\mathbf{A_i}$ on the primary contour **CP**, the 5 first values of the 6 decomposition criterions of th drawing operation: $\mathbf{R1_i}$, $\mathbf{R2_i}$, $\mathbf{r1_i}$, $\mathbf{r2_i}$, $\mathbf{H_i}$ were determined. To determine the value of the sixth criterion, the primary contour **CP** is cover, point by point, starting in $\mathbf{A_1}$, evaluating in each point the 5 first criteria. Considering it has reached the point $\mathbf{A_i}$, the values of the five criterions corresponding to point $\mathbf{A_i}$ 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 $\mathbf{A_{i+1}}$, is limiting the current area and the values of the 5 criterions, corresponding to that point ($\mathbf{A_{i+1}}$), 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 $\mathbf{A_i}$, $\mathbf{A_{i+1}}$, $\mathbf{B_{i+1}}$, $\mathbf{B_i}$. The arc length $\mathbf{A_i A_{i+1}}$ is $\mathbf{L_i}$ and represents the sixth value criterion from basic order number $\boldsymbol{i}$. In this case $\boldsymbol{n}$ areas are bounded and elementary operations are identifieded, where actual drawing operation was decomposed. The $\boldsymbol{n}$ 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 macroelements, we consider the case of a rectangular box. As shown in Figure 7, the plastic deformation of the area $\mathbf{1\text{-}A0_1\text{-}A0_2\text{-}2}$ of blank surface **SM** and the transformation of this area in $\mathbf{1\text{-}A_1\text{-}A_2\text{-}2}$ of the final part **PF** are one of the elementary deep drawing process that forms the real deep drawing process of the box, because, along the segment $A_1\text{-}A_2$, 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 $\mathbf{2\text{-}A0_3\text{-}A0_4\text{-}3}$ of blank surface **SM** in $\mathbf{2\text{-}A_3\text{-}A_4\text{-}3}$ area of final part **PF**, and their symmetrical areas represent another elementary deep drawing process.

Adding to these the transformation of the area $\mathbf{2\text{-}A0_2\text{-}A0_3\text{-}2}$ of blank surface **SM** in the area $\mathbf{2A_2\text{-}A_3\text{-}2}$ of the final part, and three identical elementary deep drawing processes corresponding to the other corners of the box, it result 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 macromodelling method determine 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, continously 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.

Acknowledgement
This research was supported by Executive Agency for Higher Education, Research, Development and Innovation Funding Grant IDEI PN-II-ID-PCE-1759 awarded to Catalina Maier.

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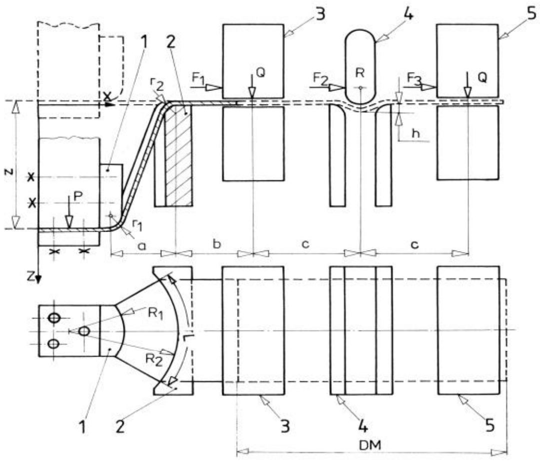

Figure 1: Generalized elementary deep drawing process
1 - punch, 2 - die, 3,5 – blankholder elements, 4 – drawbead

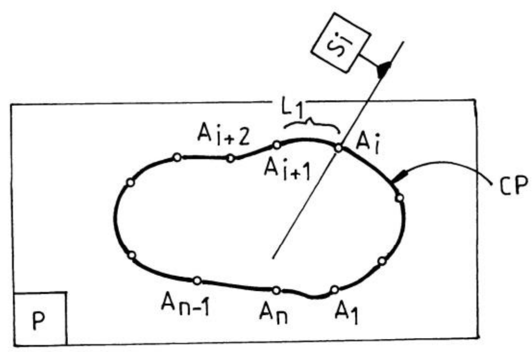

Figure 2. Primary contour line

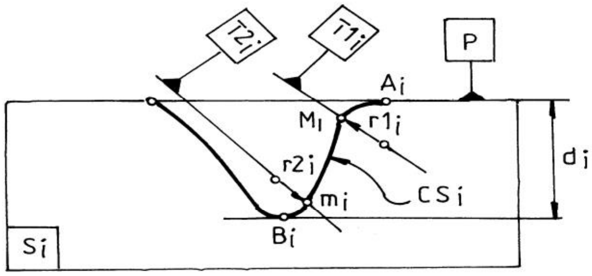

Figure 3. Secondary contour line

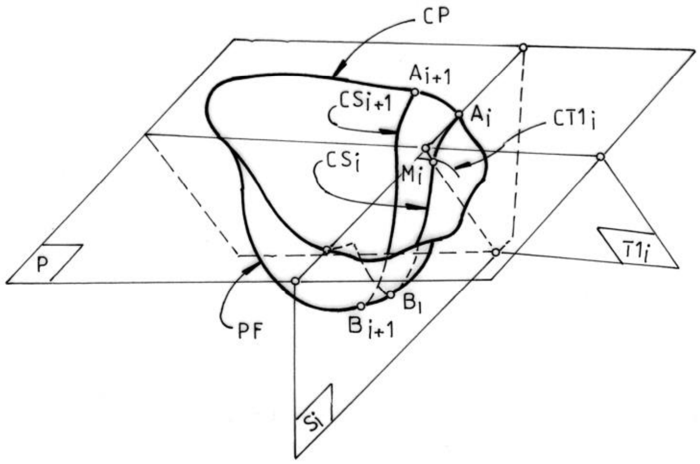

Figure 4. Cutting planes

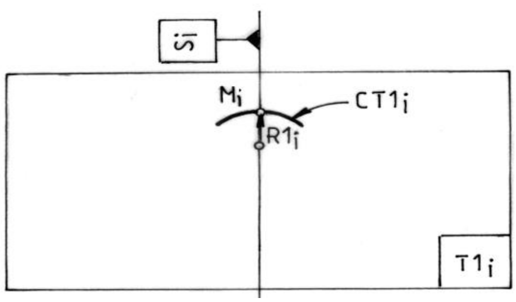

Figure 5. Tertiary contour line in the point M_i

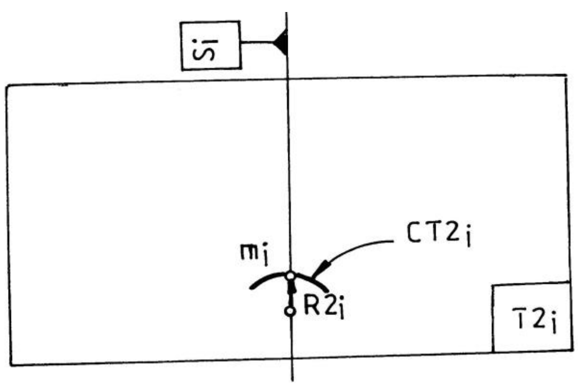

Figure 6 Tertiary contour line in the point m_i

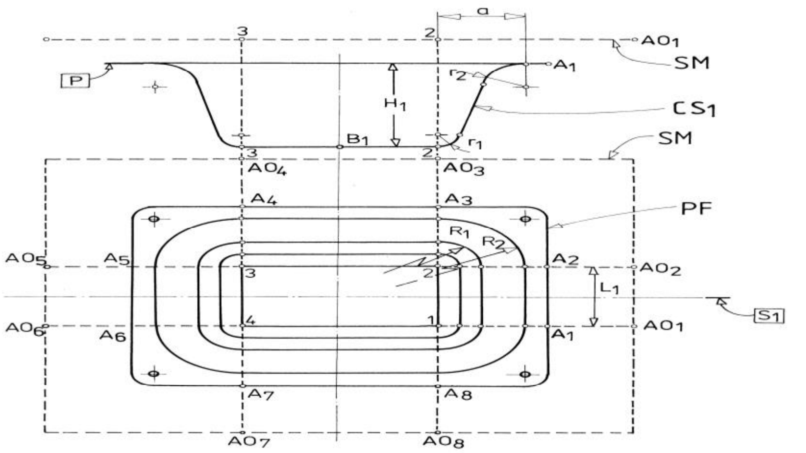

Figure 7. Case study for the rectangular box

Table 1

No.	**Specific parameter**	**Type of the specific parameter:** CG – global characteristic CL – local characteristic DG – global descriptor DL – local desciptor	**Definition**
(0)	*(1)*	*(2)*	*(3)*
1	g	CG	Thickness of the blank
2	□*c*	CG	Yield stress of the material
3	$R_{p0,2}$	CG	Tensile strength of the material
4	C	CG	Coefficient of Swift law describing mechanical behaviour of the material
5	n	CG	Coefficient of Swift law describing mechanical behaviour of the material
6	□	CG	Friction coefficient
7	R1	CL	(figure 1)
8	R2	CL	(figure 1)
9	r1	CL	(figure 1)
10	r2	CL	(figure 1)

11	H	CL	Maximal value of z (figure 1)
12	L	CL	Primary contour line dimension corresponding to the elementary deep drawing process
13	a	CL	(figure 1)
14	b	CL	(figure 1)
15	c	CL	(figure 1)
16	h	CL	Depth of drawbead penetration (figure 1)
17	Q	CL	Blankholder force (figure 1)
18	DM	DL	Displacement of free border of the blank (figure 1)
19	P	DG	Punch force
20	F1	DL	Blankholder friction force before drawbead
21	F2	DL	Drawbead friction force
22	F3	DL	Blankholder friction force after drawbead

Table 2

o. of the elementary deep drawing process	zone of the primary contour line	**local characteristic**										
		{R1} [mm]	{R2} [mm]	{r1} [mm]	{r2} [mm]	{H} [mm]	{L} [mm]	{a} [mm]	{b} [mm]	{c} [mm]	{h} [mm]	{Q} [N]
1	A_1-A_2	☐	☐	3	5	40	40	38	3	15	2	200
2	A_2-A_3	39	69	3	5	40	108,4	38	3	15	0	200
3	A_3-A_4	☐	☐	3	5	40	60	38	3	15	2	200
4	A_4-A_5	39	69	3	5	40	108,4	38	3	15	0	200
5	A_5-A_6	☐	☐	3	5	40	40	38	3	15	2	200
6	A_6-A_7	39	69	3	5	40	108,4	38	3	15	0	200
7	A_7-A_8	☐	☐	3	5	40	60	38	3	15	2	200
8	A_8-A_1	39	69	3	5	40	108,4	38	3	15	0	200