Sheet Metal Hydroforming Process Review Through Shape Factors Analysis and Numerical Simulation

DEL PRETE Antonio¹, PAPADIA Gabriele², MANISI Barbara¹
(1. Department of Engineering Innovation, University of Salento, Italy;
2. Scuola Superiore ISUFI, University of Salento, Italy)

Abstract: The increasing application of numerical simulation in metal forming field has helped engineers to solve problems one after another to manufacture a qualified formed product reducing the required time. Accurate simulation results are fundamental for the tooling and the product designs. Many factors can influence the final simulation result like for example a suitable yield criterion [1]. The wide application of numerical simulation is encouraging the development of highly accurate simulation procedures to meet industrial requirements. Currently, industrial goals of the forming simulation can be summarized in three main groups [2]: time reduction, costs reduction, increase of product quality.

Many studies have been carried out about: materials, yield criteria [3] and plastic deformation [4, 5], process parameters [6] and their optimization, geometry modifications of the stamped part to evaluate if modifications in the process responses are required, reaching the goal to perform a virtual tryout of the whole deformation process. Through a research program, whose aim is to define specific rules that allow to establish a macro-feasibility for a given hydroforming process, the authors have analyzed the influence of the process variables on sheet metal hydroforming taking into account different types of geometries. The goal of this research is to implement a methodology that allows to reach the feasibility of a product through sheet metal hydroforming starting from simple considerations in the early stage of the process design [7].

In this specific case, the developed methodology is characterized by the definition of a set of “shape factors”, purpose designed and by their application on various study cases. Their application can suggest the feasible limits for a considered process set up. Shape factors and their lower bounds have been defined through an extensive numerical and experimental investigation on three different study cases, described in recent publications by the same authors [8].

In this paper the authors aim to check the developed methodology through an application on an industrial test case characterized by a complex geometry and called “Fondello Fanale”. Starting from the geometry of the industrial test case, it is possible to say that more than one of the shape factors is needed to analyze the product feasibility. On the considered component the most critical areas have been chosen by the authors taking into account the component shape. In each one of the considered areas, the shape factors have been calculated and their value have been compared with their physical limit. The shape factors analysis has led to declare the no feasibility of the FF.

In compliance with the shape factors rules three new and different geometries have been identified and numerically tested in order to verify their feasibility.

Key words: sheet metal hydroforming, shape factors, feasibility, industrial product

Hydroforming is a forming technology for semi-finished goods like: tubes and sheets that aims to obtain high strength parts and to manufacture complex geometries in one step. Even the material straining caused by fluid pressure leads to a uniform rise in yield strength in the used materials, resulting in a lower need necessary for high wall thicknesses [9].

Nowadays the need of improving the quality and the reliability of products and of decreasing their cost represent general market requests in any field. In particular, in the automotive industry, the main aim is the reduction of CO₂ emissions and energy consumptions through the increase of the lightness of cars. In order to satisfy such targets, the attention has been recently focused on many new methods; some of them are aimed to the forming of certain lightweight metals and alloys, while other techniques are directed to a more economic components production than conventional forming methods [10].

Hydroforming allows to overcome some of the limitations of conventional deep drawing, increasing the drawing ratio and minimizing the thickness reduction of the formed parts. Some of the advantages introduced by hydroforming are: a greater flexibility and a remarkable reduction of tooling costs [11].

The basic parts of the tool for a hydroforming process include a punch, a blank holder and a fluid chamber. The draw ratio achievable in hydroforming is quite high (values of about 3,2 are reported in literature) [12], very little thinning occurs and asymmetrical shapes can be drawn.

Different studies have been conducted to design a possible classification valid for Tube Hydro Forming (THF), starting from the analysis of the shape of the formed part [13].

Though this paper only relates to Sheet metal Hydro Forming (SHF), it refers back to the above consideration about THF. The aim of this paper is to define a “shape factors” set and to direct the designer towards a proper goal in his development of the process for metal components produced through the application of sheet hydroforming. Finite Element Analysis (FEA) has been extensively used in order to
investigate and define each shape factor with a proper comparison to the macro feasibility of the chosen component geometry. In other studies, these shape factors have been also used to track the process performances through their variation thanks to the usage of the numerical simulation which has been later validated with an appropriate experimental campaign. In this paper, these parameters have been applied to a geometrical complex shape in order to investigate its own feasibility only analyzing its CAD model and to evaluate different modifications on the geometry to reach its own feasibility.

1 Shape Factors Definition and Evaluation

The shape factors are a-dimensional coefficients by which the authors want to find a connection among a shape characteristic (deep drawing depth, reverse deep drawing depth and differences in the deep drawing depth) and process set-up characteristics, such as the smallest dimension of the initial blank holder. The idea is to use shape factors to assess the “macro” feasibility of a product, through sheet metal hydroforming, starting from simple considerations about its geometry.

For a general component, obtained by hydroforming, it is possible to assume that its general sections could appear like the one reported in Fig.1. For this profile it is possible to apply the “shape factors” defined as follows:

- \( R_2 = \frac{L_2}{H_{imb}} = \frac{L_2}{A} \)
- \( R_h = \frac{L_2}{H_2} = \frac{L_2}{(A-C)} \)
- \( R_c = \frac{L_c}{H_c} = \frac{D}{(A-B)} \)

where: \( L_2 \) is the smallest dimension of the rectangle in which the initial blank is inscribed, \( H_{imb} \), which is equal to \( A \), is the maximum hydroforming depth, \( H_2 \), which is equal to \( (A-C) \), is the difference between two different hydroforming depths that characterizes the product and, finally, \( L_c \), which is equal to \( D \), is the minimum dimension, in top view, of the reverse deep drawing and \( H_c \), which is equal to \( (A-B) \), is the depth of the reverse deep drawing.

The authors’ aim is to find through the use of shape factors, feasible limits for the process by analyzing the thickness distribution in function of \( R_2 \). Through this work it is possible to determine, for a fixed geometry, the maximum deep drawing depth required to obtain the product feasibility. Likewise, analyzing the thickness distribution in function of \( R_h \), it is possible to determine the maximum difference in the deep drawing depth and finally, analyzing in the same way \( R_c \), it is possible to determine the maximum reverse deep drawing depth that assures the product feasibility.

Different values can be considered for the shape factor \( R_h \). In fact, since \( H_2 \) is the difference between two different hydroforming depths, for the generic component in Fig.1, different values of \( H_2 \) equal to \( (A-C) \) or \( (A-B) \) can be defined.

For a generic geometry as illustrated in Fig.1, it is possible to define all of the afore-mentioned three shape factor simultaneously.

The purpose of the shape factors application is to verify product feasibility in the process development starting phase through geometrical considerations, without the execution of numerical simulations.

To determine the shape factors reference values, the authors have studied three simple geometrical models, manufactured by hydroforming. These three reference models have been named, respectively, as MOD1, MOD2 and MOD5 as reported in Fig.2.

For each one of them it is possible to associate and calculate one of the generic shape factors defined for the generic profile reported in Fig.1. In particular, MOD1 is related to \( R_2 \), MOD2 to \( R_h \) and, finally, MOD5 to \( R_c \) (Fig.2).

For every shape factor the authors have calculated a limit value under which the component feasibility becomes critical:

- For MOD1 the \( R_2 \) critical value (\( R_2^{cv} \)) is 4.
- For MOD2 the \( R_h \) critical value (\( R_h^{cv} \)) is 19.1.
- For MOD5 the \( R_c \) critical value (\( R_c^{cv} \)) is 10.

If the shape factor decreases under this limit value, the product is not feasible for the given process parameters.
The implemented methodology can be summarized by the following sentence: “Considering a generic geometry that has to be manufactured by sheet metal hydroforming, it is possible to verify its feasibility through simple geometrical considerations.

In relation to the presence, in the analyzed geometry, of one or more deep drawing depths, just one of them or all the shape factors $R_3$, $R_h$, and $R_c$ have to be calculated. The geometry is feasible if all the shape factors have a magnitude that is higher than their previously calculated limit values. If just one of them goes under its lower limit, then the product is not feasible and it is necessary to check the possible feasibility in a numerical way. If the analyzed geometry is very complex, it is possible to calculate the shape factors in different sections of the geometry itself. In this case, to reach the feasibility of the analyzed product, it is necessary that in each section all the shape factors calculated have a magnitude that is higher than their limit values”.

2 Application of Shape Factors to an Industrial Case

To check the methodology previously illustrated, the authors have applied it on an industrial test case called Fondello Fanale (FF), which is characterized by a complex geometry and currently manufactured by two conventional deep drawing steps.

The complex geometry of FF has entailed to take into account all the shape factors previously calculated. As far as $R_2$ is concerned, the inconstancy of the drawing depth of the FF has led the authors to choose the maximum drawing depth of 78 mm for the $H_{imb}$, as depicted in the following relationship:

$$R_2 = \frac{L_2}{H_{imb}}$$

where $L_2$ is equal to 490 mm (the smallest dimension of the rectangle in which the initial blank is inscribed). By this way, the value of 6,3 previously calculated for $R_2^{FF}$ is the minimum possible value for the shape factor $R_2$ considering the FF geometry.

$R_2^{FF}$ is greater than $R_2^{cv}$, so the product is feasible if the only $R_2$ value is considered.

Because of the complex geometry of the FF, it is necessary to choose on it some sections where to calculate the other shape factors and where to verify the feasibility conditions. The authors have defined the most critical reference sections (that are indicated in Fig.3) through a CAD analysis. Just as explained in a traditional study about the macro feasibility of a product, the process designer can perform an analysis of the geometry making sections in the area that are with an high deep drawing depth or characterized by an high variation of the surfaces.

Due to the FF geometry complexity, more than a single $R_c$ or $R_h$ shape factor can be defined for each section. For example, in Fig.3a) it is possible to calculate an $R_c$ equal to 3,0 ($=126,3/41,8$) and an $R_c$ equal to 1,1 ($=55,4/50,2$).

For each section taken into account, the values of the single shape factors are reported in Fig.3.

The value of the most critical factors can be determined from the following relationship:

- $R_3^{(AA)} > R_3^{(DD)} > R_3^{(CC)} > R_3^{(BB)} > R_3^{(CC)} \Rightarrow R_3^{(CC)} = 1,2$ is the $R_3$ most critical factor,
- $R_3^{(DD)} > R_3^{(AA)} > R_3^{(CC)} > R_3^{(BB)} \Rightarrow R_3^{(BB)} = 6,7$ is the $R_3$ most critical factor.

Finally, it can be written that:
- $R_2^{(AA)} > R_2^{cv}$ (in fact 6,3 > 4) $\Rightarrow$ feasibility;
- $R_3^{(CC)} < R_3^{cv}$ (in fact 1,2 < 10) $\Rightarrow$ no feasibility;
- $R_3^{(BB)} < R_3^{cv}$ (in fact 6,7 < 19,1) $\Rightarrow$ no feasibility.

So, the FF is not feasible by a single hydroforming step with given process parameters and it is necessary to check the possible feasibility in a numerical way.

3 Fondello Fanale Re-design
In order to reach the macro feasibility of FF by using the shape factors methodology, the authors have re-designed the FF geometry, starting from the limit values previously calculated.

Among all defined shape factors, $R_2^{FF}$ is not critical for FF feasibility as illustrated in Fig. 3. On the contrary, $R_c^{FF}$ and $R_h^{FF}$ factors are very critical. An important analysis of the component geometry has been required in order to conform FF shape factors’ values with critical values calculated for MODi.

![Fig. 3](image)

**Fig. 3** a) $R_c$ and $R_h$ shape factors for AA section, b) for BB section, c) for CC section, d) for DD section

Studying the different possibilities about the FF re-design, it is necessary to highlight the final product, which is reported in Fig. 4 as FF element (in blue). The latter is obtained after a trimming operation on the FF hydroformed geometry. The final shape of the trimmed part cannot be changed due to its final application. From this point of view it is clear that the three following hypothesis for FF re-design (Fig.4) have been obtained only through a geometrical modification of the “addendum”, which is highlighted in Fig.4 in yellow.

![Fig. 4](image)

**Fig. 4** FF element in original punch and a punch

From the previous analysis on the original geometry it has been obtained that the section with the most critical values for the shape factors is the BB one (Fig.3), which has been taken into account as “the reference section” in the FF re-design. In relation to BB, the new geometry of the addendum has been designed through a trial and error technique, based on the calculation and recalculation of the shape factors. As result a new possible shape named Designa has been obtained (Fig.5). The calculated shape factors for
the so obtained shape (Table 1) are the following:

\[ R_2^\alpha = \frac{L_2}{H_{imb}} = 9.6; \quad R_\alpha^h = \frac{L_2}{H_2} = 50; \quad R_c^\alpha = \frac{L_c}{H_c} = 10.1 \]

All Design\(\alpha\) shape factors values are higher than their critical values so the \(\alpha\) geometry can be considered feasible from a "macro" point of view.

<table>
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<tr>
<th>Geometrical parameters to calculate the shape factors for the shapes (\alpha), (\beta) and (\gamma)</th>
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<tr>
<td>(L_2) [mm]</td>
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The second geometry, named Design\(\beta\), has been obtained starting from the \(\alpha\) geometry reducing its addendum area. The values of the Design\(\beta\) shape factors are: \(R_2^\beta = \frac{L_2}{H_{imb}} = 6.6, R_\beta^h = \frac{L_2}{H_2} = \infty\) (in fact \(H_2 = 0\)), \(R_c^\beta = \frac{L_c}{H_c} = \infty\).

Comparing \(R_2^\beta\) with its critical value, it results that \(R_2^\beta\) is greater than \(R_2^{\alpha}\). Furthermore, \(R_\beta^h\) and \(R_c^\beta\) factors can be assumed as analytically infinite (Table 1), and, consequently, greater than the critical shape factors values, in line with the aim of the FF re-design.

Finally, the third geometry, named Design\(\gamma\), has been re-designed in order to obtain a geometry as similar as possible to the original FF, but with a simpler and more regular addendum area. The values of the Design\(\gamma\) shape factors are: \(R_2^\gamma = \frac{L_2}{H_{imb}} = 9; R_\gamma^h = \frac{L_2}{H_2} = 27.5; R_\gamma^c = \frac{L_c}{H_c} = 1.3\).

\(R_2^\gamma\) and \(R_\gamma^h\) shape factors are less than their critical values so the \(\gamma\) geometry is not feasible.

### 4 Numerical Results

The results of the numerical analysis for the FF new geometries are described in this paragraph.

The Design\(\alpha\) FLD (Fig. 8 a) shows the absence of failures but some wrinkles in the addendum area, which do not affect the feasibility of the designed shape, therefore Design\(\alpha\) can be declared feasible. Wrinkles are due to an excess of material, which depends on three variables related to each other: pre-bulging height, fluid pressure and blank holder force. Blank holder force is also given by 12 independent actuators that must be controlled in line with fluid pressure load paths. These considerations highlight the difficulty in managing the process and its feasibility.

Fig. 8 b) shows the FLD obtained for the Design\(\beta\). It is possible to observe absence of failures and
wringles, therefore Designβ can be declared feasible. As reported in Table 1, Rbβ and Reβ can be assumed analytically infinite, therefore greater than their critical geometries manufactured by hydroforming.

In the specific case of Fondello Fanale (FF), the complex geometry has requested to apply all the defined shape factors, which have demonstrated the no-feasibility of FF.

For this reason, a re-design of FF has been taken into account. Three new geometries have been defined and numerically investigated reaching a feasible configuration for two of them.

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5 Conclusions and Further Developments

The implemented shape factors theory gives the chance to analyze the macro feasibility of a shape manufactured by sheet metal hydroforming in an early stage of the process development. In fact, in order to apply the previously illustrated methodology, a simple geometrical analysis of the given component is enough to calculate its shape factors. The product is feasible if all the shape factors have magnitude higher than their limit values, which have been calculated by the authors through a numerical and experimental investigation about the feasibility of simple geometries manufactured by hydroforming.

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Fig. 8c) reports Designγ FLD, and it is possible to observe failure zones in the punch radius area. In fact the sheet finds it hard to flow under the punch radius, also because it is pushed against the punch by the fluid pressure, thus creating failure zones.

This case is a further validation of the influence of shape factors on the product’s feasibility. In fact, Rγ results less than its critical value thus the β geometry is not feasible.

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process parameters, Report No. ERC/NSM-98-R-34, The Ohio State University, Columbus, OH, October 1998.