Theory and mechanical analysis of Tube Hydroforming of hollow component

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Abstract. Tube hydroforming is efficient plastic technology in manufacturing hollow components and is attracting more attention in the past decades. In this paper, the mechanical theory of hydroforming was studied. The external load character and internal stress character of tube hydroforming were discussed. Then, according to the characters, the function and classification of internal pressure were presented in general. Base on the stress analysis, its effect on the yield criterion and calculation formula were also researched and derived. It demonstrates that processing parameter plays an important role in tube hydroforming and formula discussed and derived by this paper is feasible in practice.

Key word: Tube hydroforming; stress state; theory analysis; hydroforming formula.

1. Introduction
Tube hydroforming is a kind of soft-tool forming technology and developed rapidly in the past decades. For taking tubes as processing blanks and liquid as flexible punch, it is more suitable for manufacturing special tubular components, such as different kinds of hollow shafts, discharge pipe of automobile & aeroplanes, sectional pipe and so on[1-4].

Compared with traditional processing technology, tube hydroforming always manufactures components in one step. So it can enhance part quality, such as tighter tolerance & increased rigidity, and lower production costs, reduction in production cycle and fewer dies, greatly.

With the special advantages, since 1990’s, tube hydroforming begins to attract dramatic attention from scientist to engineers and developed rapidly. A series of seminar and academic congress had been organized in USA & Europe, and special manual has even been published in Germany. Many commercial finite-element softwares have taken it as a main function of the codes and a large number of foundations from the government had been appropriated for it. Especially in automobile industry, most of the famous automotive corporation, such as DAIMLER BENZ and GM, are adopting it as a potent means in strengthening their competitive power in the market[5-10].

Fig.1 is the schematic diagram of the process. Tubes were placed in the die and sealed on the end firstly. Then under the co-action of compressive axial force and internal pressure, it is forced to deform from elastic stage to plastic stage. With the increasing of the applied load, the deformation increased correspondingly. Finally, under the extremely high pressure, the tube assumed the internal contour of the die precisely.
In this paper, aimed at the problem of parameter’s selection, by establishing the relationship between microscopic stress state and macroscopic deformation, the effect of processing parameter was discussed and analyzed. The result demonstrates that theory and formula presented in this paper are rational in theoretical analysis.

2. Characteristics of internal stress
Stress state is determined by external load. According to the external load character, the stress state of tube hydroforming is three-dimensional.

Axial compression force gives rise to axial compression stress and internal pressure created circumference tensile stress and radial compression stress. The blank was under the state of two compression stress & one tensile stress state and Fig.2 is the corresponding stress state diagram.

Axial compression stress is always remarked as $\sigma_z = \frac{F}{S}$, which is the quotient of axial compression force F and the action area of the axial force, S. Circumference tensile stress and radial compression stress are always denoted as $\sigma_\theta = \frac{PR}{t}$ and $\sigma_r = P$, where P, R and t are the internal pressure, radius, thickness of the blank respectively.

3. Characteristics of the external load
Tube hydroforming is plastic forming technology, the deformation of the blank and the mechanical character of the process are all determined by the external load. It is the external load character that determined what shape will the blank assumed and if the component can satisfy the design criterion.

From the discussion of Fig.1 we can find, in fact the external load of tube hydroforming consists of three parts, axial compression force, internal compression pressure and friction between the die and the blank.

The different combination of the forces created different shape of the components and the different external force plays different roles and assumed different character during the process.
Axial compression force is mainly used to seal internal liquid and provide axial supplement, so it is the first external force that act on the blank and the last force to withdraw. With the development of the process, it assumed a n-shape curve, take the largest value during the process of axial supplement.

Internal compression pressure provides the force for bulging and presents quasi-linear shape. It acts on the blank after the axial seal and then increased monotone until the completion of the process. Of course, with the end of a production cycle, the internal compression pressure also decreased and started subsequently in the next production cycle.

Of all the three external loads, friction is the only one that is not active load. It acts on the blank with the starting of axial supplement and increases with the increasing of the internal pressure. It just acts on the part of the blank that contact with the die and disappeared when there are no relative shift between the die and the blank. So it’s tribological mechanism is very sophisticated and up to now there are still no satisfied theory to unpuzzle its mechanics. For it is not a active load on the blank and comparing with other two external load its influence is relative low, according to research convention, it is ignored to be considered in this paper.

4. Effect on the Yield Criterion
During plastic deformation stage, the deformation of the materials is controlled by yield criterion flow stress. The action of internal pressure on the process is also through the yield criterion flow stress.

Equation (1) is the expression of Misses yield criterion, which is the most general yield criterion of plasticity.

$$\sigma_i = \frac{1}{\sqrt{2}} \sqrt{(\sigma_\theta - \sigma_i)^2 + (\sigma_i - \sigma_z)^2 + (\sigma_z - \sigma_\theta)^2} = \sigma_s$$  \hspace{1cm} (1)

Where $\sigma_\theta, \sigma_i, \sigma_z$ are the primary stress components separately and $\sigma_i$ and $\sigma_s$ are the equivalent stress and yield stress of the blank.

The expression shows that, there are two stresses, $\sigma_\theta$ and $\sigma_i$ are determined by internal pressure. The increasing of the internal pressure gives rise to not only the increasing of $\sigma_i$ but also $\sigma_\theta$, any variation of the internal pressure all affects the yield criterion doubly.

So to make it convenient for analyzing, according to the classification of the internal pressure, equation (1) was simplified as equation. (2) & (3) and discussed respectively as follow:

$$\sigma_i = \frac{1}{\sqrt{2}} \sqrt{2(\sigma_\theta - \sigma_i)^2} = \sigma_s$$ \hspace{1cm} (2)

$$\sigma_i = \frac{1}{\sqrt{2}} \sqrt{2(\sigma_\theta - \sigma_z)^2} = \sigma_s$$ \hspace{1cm} (3)

During the initial stage, $\sigma_i$ is relatively low, so it is omitted in the formula. By substituting it with zero, Eq. (1) was simplified as Eq. (2). The expression of Eq. (2) shows that, during the initial stage, $\sigma_\theta$ and $\sigma_z$ are the main stresses which influence the deformation of the blank, and they presented inverse relation during the process. With the internal pressure increasing, $\sigma_z$ decreased correspondingly and vice versa.

5. Calculation and application
Internal pressure affects the deformation of the blank by yield criterion and it is controlled by external load. But in practical process, formula of the internal pressure calculation is more valuable.

For the blank of tube hydroforming, the stress should satisfy the balance differential equation and under the cylindrical coordinates it can be expressed as Eq. (4).
\[
\frac{\partial \sigma_r}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\partial \tau_{rz}}{\partial z} = 0
\]

\[
\frac{\partial \tau_{r\theta}}{\partial r} + \frac{1}{r} \frac{\partial \sigma_r}{\partial \theta} + \frac{\partial \sigma_z}{\partial z} = 0
\]

\[
\frac{\partial \tau_{r\theta}}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\tau_{zz}}{r} = 0
\]

Considering the symmetrical character of the blank, and if the component is also symmetry, it can be simplified as Eq. (5).

\[
\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} = 0
\]

\[
\frac{\partial \tau_{r\theta}}{\partial r} + \frac{\partial \sigma_z}{\partial z} = 0
\]

For the thickness of the blank and the component is always relatively thin, if cut a cell cube from the blank and set up the balance equation, Eq. (5) can also be simplified as Eq. (6) and (7)

\[
\sigma_r rdz - \sigma_{r\theta} d\theta dz = 0
\]

\[
\sigma_{r\theta} - \frac{Pr}{t} = 0
\]

Equation (7) is an equation about the pressure and internal stress, so it is just the calculation formula of internal pressure.

However, as a formula derived under hypothesis, corresponding experiments were necessary to see if the formula is correct in practical applications.

To prove the effect of above formula, the result of above discussion was used in the processing design of hollow component as shaft. Fig.3 is the geometrical prototype of the component and blank. From hollow tube, the final component is hollow shaft as fig.3.

![Fig. 3 Geometrical prototype of experimental three-diameter shaft and blank](image)

(a) three-diameter shaft (b) blank

With the proper design of the process, the hollow component as shaft was manufactured finally, which proved the advantage of the formula developed above.

6. Conclusion

In this paper, tube hydroforming was investigated theoretically. According to the external load character and internal stress character of tube hydroforming, the function and classification of internal pressure was introduced. Then, its effect on the yield criterion and calculation formula was analyzed and derived. Based on the calculation formula, experiment with different internal pressure was carried out and the result was discussed. Through the discussion, the following conclusions are drawn:(1) Internal pressure
generates circumference tensile stress and radial compression stress, it is the reason of circumference
tensile strain and radial displacement.(2) During the process, internal pressure always experienced two
stages, initial low pressure stage and ultimate high pressure stage.(3) Of the initial stage, it is mainly to
fill materials up to the die properly and during the ultimate stage it is mainly to press the blank to assume
the internal counter of the die.(4) The action of internal pressure on the process is through the yield
criterion and yield criterion can be simplified as different style during the different stage.

Acknowledgements
This research was financially supported by the Dongguan Innovation and Entrepreneurship Leadership
Program Funding.

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