

Analytical Model for Bi-Layer Tubes Hydro Forming Process and **Its Experimental Inspection**

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ABSTRACT

In this paper inspection of tube hydro forming process in order to estimate the governing parameters on the process such as internal pressure and axial force have been done. By simplify the governing equations on both thin and thick wall cylinders and Von-Maises theory, the amount of internal pressure and axial force have derived. In order to experimental validation, the necessary die and supporting system package for produce a sample part was designed and made. The final sample part was produced successfully based on theoretical result by using mentioned die and supporting system. KEY WORDS: bi-layer tube hydro forming, analytical relations, loading path

INTRODUCTION

However, industrial development of hydro forming process has began from 1980, it has a long background. In 1903 the first necessary instrument for forming a hollow spiry part which is used in boiler system was invented by Park. An overall study was done on hydro forming process in 2000. In 2006 M.D.Islam and coworkers inspect the possibility of forming the multilayer tubes components by hydro forming process, and its finite element simulation. The simulation results will be approved by experimental results. In this paper the necessary equations for estimate the effective parameters on hydro forming of bi-layer tubes are inspected. Effective parameters on hydro forming process and its governing equations. In order to produce a part with out any defect and with sufficient coordination, the internal pressure path (curve) Vs time during the process should be take in account and so the axial force path Vs time should be determined.(the pressure Vs process time curve shape). Achieving this favorite is impossible with out determined the loading path. By determination sealing pressure, yielding pressure, bursting pressure and calibration pressure the loading path will be determined. In the fallowing section each parameters will be derived and use in determination of loading path. Internal pressure:

As the best approach for understanding the parameters of hydro forming process, the diagram of pressure Vs time should be calculated and so proportional to it the axial force Vs process time should be designed.

If parameters be out of safe region of forming during the process, wrinkling, buckling and bursting may be occurred.

Hydro forming process included 2 main steps: the former is the free forming and the latter is the calibration step.

In fact the free forming pressure means pressures which in part touch the central points of die and calibration pressure means pressures which in part fill the corner of die.

It should be mentioned that, in this calculation Levy-Maises flow rule ans Von-Maises yielding criterion are used.

By using membrane theory, internal pressure in a thin layer tube can be referred longitudinal and hoop stress as fallow: EO1

$$\frac{\sigma_1}{\rho_1} + \frac{\sigma_2}{\rho_2} = \frac{p}{t} \tag{1}$$

Membrane equation is achieved from equilibrium equation and valid for both elastic and plastic state. In above equation φ and φ^2 are the smaller and larger element radiuses respectively; P and t are instant pressure and thickness. Now review some essential equations: EO2

$$\beta = \frac{\varepsilon_2}{\varepsilon_1}, \ \alpha = \frac{\sigma_2}{\sigma_1} \tag{2}$$

Principal strains included hoop strain, longitudinal and radial will be:EQ3

$$\varepsilon_1 = \ell n \frac{\rho_1}{\rho_0}, \varepsilon_2 = \ell n \frac{l_1}{l_0} = \beta \varepsilon_1, \varepsilon_3 = \ell n \frac{t_i}{t_0} = -(1+\beta)\varepsilon_1$$
(3)

Above strains are actual strains and are used in plastic state. Considering Love-Maises flow rule, stress to strain ratio (in plastic state) will be related to each other as fallow:EQ4

$$\beta = \frac{2\alpha - 1}{2 - \alpha}, \ \alpha = \frac{2\beta + 1}{2 + \beta} \tag{4}$$

The Von-Maises yielding criteria (simple stress) and its respected strains as: EQ5 EQ6

$$\overline{\sigma} = \sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2} = (\sqrt{1 - \alpha + \alpha^2})\sigma_1 = \sigma_f \quad (5)$$

$$\overline{\varepsilon} = \frac{2}{\sqrt{3}} (\sqrt{1 + \beta + \beta^2}) . \varepsilon_1 \tag{6}$$

With combining equation 5 & 2 and 1 can write EQ7

$$P = t(\frac{1}{\rho_2} + \frac{1}{\alpha\rho_1})\sigma_2 \Longrightarrow$$

$$P = \frac{\overline{\sigma}}{\sqrt{1 - \alpha + \alpha^2}} t \cdot (\frac{1}{\rho_1} + \frac{\alpha}{\rho_2}) = \frac{\overline{\sigma}}{\sqrt{1 - \alpha + \alpha^2}} t \cdot (\frac{1}{\rho_2} + \frac{1}{\alpha\rho_1})$$
(7)

Which P is the instant pressure.

Internal pressure calculation:

In order to achieve governing equations for bi-layer tube extension the bellow assumptions are considered:

Both tubes are stick together on touching surface and there are no separation along common surface, so the contact pressure (P contact) will be performed uniformly on both inner surface of external tube and outer surface of internal one. As shown in figure 1, the forming pressure is applied on inner surface of internal tube. On the other statement, the total pressure provided by hydraulic pump is applied on internal tube and the forming pressure of external tube is equal to the contact pressure and forming pressure for internal one is (P forming _P contact).

Both of tubes remain cylindrical during the forming process and would have; EQ8, FIG1



fig. 1inner and outer tubes

Internal pressure calculation in the presentation of axial force; elastic state:

In order to calculate the internal pressure in elastic state, it is necessary to calculate the sealing and yielding pressure. The internal pressure should be at least as much as can prevent buckling and wrinkling of tube which is caused by performing axial force that is needed for sealing. This pressure can be calculated by considering the equilibrium equations for performed forces on internal and external tubes according to figure 2.



At first we suppose that the force on both tubes is as much as they tend to buckle to inside direction which causes an contacting pressure (P contact) between two tubes which actually prevents buckling on external tube and its reaction is applied on internal tube, so the initial internal pressure should be as much as can not only compensate the contact pressure but also prevent buckling of internal tube. We suppose for both tubes that the amount of buckling (X) is equal to thickness of each tube (t_i, t_o) .

Sealing pressure of external tube: EQ 9

$$P_{contact}A_o = 2F_o tg \beta$$

$$P_{contact} \times 2\pi r l = 2F_o t_o/l_o$$
(9)

 F_0 is the axial force on external tube which equals the initial sealing force of external tube walls. Now by considering the equation No:9, the minimum initial pressure for external tube would be : EQ 10

$$P_{cont} = 2\sigma_{oy} (\frac{t_0}{L_0})^2 = 2\sigma_{oy} (\frac{t_0}{L})^2$$
(10)

In above relation L_0 is the initial length of external tube which is as same as initial length of internal tube, so we will use L for length of both tubes in final equation. Internal tube: EQU 11, 12

 $(p_i - P_{con})(2\pi r l)_i = 2F_i t_i / l_i$ (11)

$$F_i = 2\pi r_i t_i \sigma_{i_{\mathcal{V}}} \tag{12}$$

That F_i is the applied axial force on internal tube which is as much as initially sealing force of internal tube. By using equations 11 & 12 the minimum initial pressure for internal tube will be: EQ13

$$P_{i} - P_{cont} = 2\sigma_{iy} (\frac{t_{i}}{L_{i}})^{2} = 2\sigma_{iy} (\frac{t_{i}}{L})^{2}$$
(13)

And then by combining equation 10 & 13 will have: EQ14

$$(P_i)_{\min} = 2\sigma_{iy} (\frac{t_i}{L})^2 + 2\sigma_{oy} (\frac{t_0}{L})^2$$
(14)

That $(P_i)_{min}$ is the minimum initial pressure which has to apply on inner surface of internal tube in order to prevention of buckling on both internal and external tubes which is caused by applied axial force (sealing factor for both tube versus initial seal).

After that we have to calculate the pressure that in both tubes will be on the threshold of yielding. Yielding pressure: P_{iv}

The below equations are governed on external tube on the threshold of yielding

$$\rho_{o1} = (D_{o0} - t_{o0})/2, \rho_{o2} = \infty, t_o = t_{o0}, \overline{\sigma} = \sigma_{oy}$$
(15)

Which t_{o0} is the initial thickness of tube and t_o is in instance of yielding By considering the equation 7 & 15 we have:

$$P_{oy} = (P_{cont})_{y} = \frac{\sigma_{oy}}{\sqrt{1 - \alpha_{o} + \alpha_{o}^{2}}} \cdot \frac{2t_{o0}}{(D_{o0} - t_{o0})}$$
(16)

And by merging equation 14&16:

$$P_{iy} = \frac{\sigma_{iy}}{\sqrt{1 - \alpha_i + \alpha_i^2}} \cdot \frac{2t_{i0}}{(D_{i0} - t_{i0})} + \frac{\sigma_{oy}}{\sqrt{1 - \alpha_o + \alpha_o^2}}$$

$$\cdot \frac{2t_{o0}}{(D_{o0} - t_{o0})}$$
(16)

In this equation P_{iy} is the pressure in instance of yielding or yielding pressure which has to apply on internal surface of inner tube in order to put them on threshold of yielding.

Bursting pressure:

The needed pressure for plastic deformation, with suppose that tubes remain cylindrical during the process will be investigated. This assumption means that for both tubes $\varphi_2=\infty$, FIG3



Fig. 3

So the equation 7 will changed to Equ17

$$P = \frac{\overline{\sigma}}{\sqrt{1 - \alpha + \alpha^2}} \cdot \frac{t}{\rho_1} \tag{17}$$

That t is the instant thickness and according to equation 3: EQU 18

$$\rho_1 = \rho_0 e^{\varepsilon_1} t = t_0 e^{-(1+\beta)\varepsilon_1} \Longrightarrow \frac{t}{\rho_1} = \frac{t_0}{\rho_0} e^{-(2+\beta)\varepsilon_1}$$
(18)

Now by considering the equation 17& 18 final pressure equations in plastic state will be as fallow: For external tube: Instant radius of external tube is: EQU 19 & 20

$$P = \frac{\overline{\sigma}}{\sqrt{1 - \alpha + \alpha^2}} \cdot \frac{t_0}{\rho_o} e^{[-(2 + \beta)\varepsilon_1]}$$
(19)

$$\rho_{o1} = \frac{d_o - t_o}{2} \tag{20}$$

That in, d_0 and t_0 are the instant diameter and thickness of external tube respectively. Now the equation 17 will be written as fallow by combining with equation 20 & 6 and Paverla rule: EQU 21 & 22

$$P_{o} = P_{cont} = \frac{2t_{o}K_{o}\varepsilon_{o1}^{no}}{(d_{o} - t_{o})\sqrt{1 - \alpha_{o} + \alpha_{o}^{2}}} \times \left[\sqrt{\frac{4}{2}(1 + \beta_{o} + \beta_{o}^{2})}\right]^{no}$$
(21)

$$\varepsilon_{o1} = \ell n \left(\frac{\rho_{o1}}{\rho_{o0}} \right) = \ell n \left[\frac{d_o - t_o}{D_{o0} - t_{o0}} \right]$$
(22)

By merging the equations 22 & 4 in equation 21, another statement of final equation of pressure in plastic state for external tube will be achieved: EQU 23

$$P_o = P_{cont} = \frac{2t_o}{d_o - t_o} K_o \left(\frac{2}{2 - \alpha_o}\right) \times$$

$$^{no} \left(\sqrt{1 - \alpha_o + \alpha_o^2}\right)^{no-1} \left(\ell n \frac{d_o - t_o}{D_{o0} - t_{o0}}\right)^{n0}$$
(23)

For internal tube:

The instant radius of internal tube is EQU 24

$$\rho_{i1} = \frac{d_i - t_i}{2} \tag{24}$$

By merging the equations 24 & 6 and Paverla rule, the equation 17 will be: EQU 25

$$P_{i} - P_{cont} = \frac{2t_{i}K_{i}\varepsilon_{i1}}{(d_{i} - t_{i})\sqrt{1 - \alpha_{i} + \alpha_{i}^{2}}} \times \left[\sqrt{\frac{4}{3}(1 + \beta_{i} + \beta_{i}^{2})}\right]^{ni}$$
(25)

Now according to equation 3 & 24 will have: EQU 26

$$\varepsilon_{i1} = \ell n(\frac{\rho_{i1}}{\rho_{i0}}) = \ell n \left[\frac{d_i - t_i}{D_{i0} - t_{i0}} \right]$$
(26)

By merging equations 26 & 4 in 25, another statement of final pressure equation in plastic state for internal tube will be achieved EQU27

$$P_{i} - P_{cont} = \frac{2t_{i}}{d_{i} - t_{i}} K_{i} \left(\frac{2}{2 - \alpha_{i}}\right)^{ni} \times \left(\sqrt{1 - \alpha_{i} + \alpha_{i}^{2}}\right)^{ni - 1} \left(\ell n \frac{d_{i} - t_{i}}{D_{i0} - t_{i0}}\right)^{ni}$$
(27)

Next by merging equations 23&27: EQU 28

$$P_{i} = \frac{2t_{i}}{d_{i} - t_{i}} K_{i} \left(\frac{2}{2 - \alpha_{i}}\right)^{ni} \times \left(\sqrt{1 - \alpha_{i} + \alpha_{i}^{2}}\right)^{ni-1} \left(\ell n \frac{d_{i} - t_{i}}{D_{i0} - t_{i0}}\right)^{ni} + \frac{2t_{o}}{d_{o} - t_{o}} K_{o} \left(\frac{2}{2 - \alpha_{o}}\right)^{no} \left(\sqrt{1 - \alpha_{o} + \alpha_{o}^{2}}\right)^{no-1} \left(\ell n \frac{d_{o} - t_{o}}{D_{o0} - t_{o0}}\right)^{n0}$$
(28)

That the achieved pressure is the final pressure in plastic state which means that pressure as much as P_i is required for forming of both tubes.

Calibration pressure:

The best way in order to estimate the maximum internal pressure which is needed for both tubes to fill the corners of die is modeling the corners of tube as a thick wall cylinders same as figure 4. it is because that the ratio of radial to thickness is less than 10 in these regions. So the maximum pressure should be calculated according to equations of thick-walled cylinders. Here we use Tereska criteria for our calculations. Fig4



Fig. 4

For such as cylinders according to figure 5: EQU 29

$$\sigma_{r} = \frac{r^{2}{}_{a}r^{2}{}_{b}(P_{b} - P_{a})}{r_{b}^{2} - r_{a}^{2}} \cdot \frac{1}{r^{2}} + \frac{P_{a}r_{a}^{2} - P_{b}r_{b}^{2}}{r_{b}^{2} - r_{a}^{2}}$$

$$\sigma_{\theta} = -\frac{r^{2}{}_{a}r^{2}{}_{b}(P_{b} - P_{a})}{r_{b}^{2} - r_{a}^{2}} \cdot \frac{1}{r^{2}} + \frac{P_{a}r_{a}^{2} - P_{b}r_{b}^{2}}{r_{b}^{2} - r_{a}^{2}}$$
(29)



That in r_a and r_b are respectively inner and outer radius of cylinder and P_a and P_b are internal and external pressure of thickwalled cylinder respectively. These amounts are achieved based on if strain situation is flat or the axial strain is zero any where.

By introducing the Tereska criteria and assume that $(\sigma_{\theta} - \sigma_r)$ is the largest differences between major stresses: EQU 30

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_{\theta}}{r} = 0 \Longrightarrow \frac{d\sigma_r}{dr} - \frac{Y}{r} = 0$$
(30)

If we suppose that the internal pressure in a single layer tube is as much as can cause plastic yielding in this tube until radius C, so we will have EQ 31

$$\sigma_r = Y\ell nr + C_1 \tag{31}$$

Because in the radius $r=r_a$ the stress is $\sigma_{r=}-p_a$ so: EQ 32

$$\sigma = Y \ell n \frac{r}{r_a} - P_a \tag{32}$$

And stress for r=c will be: EQ 33

$$\sigma_c = Y \ell n \frac{r_c}{r_a} - P_a \tag{33}$$

By merging the equations 29 & 30 for elastic region will have: EQU 34



And by eliminating σ_c from equation 33 & 34 achieve the fallow results: EQU 35

$$P_{i} = Y \ell n \frac{r_{c}}{r_{a}} + \frac{Y(r_{b}^{2} - r_{c}^{2})}{2r_{b}^{2}}$$
(35)

In this equation we suppose that $P_b=0$ in other wise if $P_b\neq 0$ so: EQU 36

$$P_a - P_b = Y \ell n \frac{r_c}{r_a} + \frac{Y(r_b^2 - r_c^2)}{2r_b^2}$$
 (36)

In order to entering the tube completely to plastic state, it is necessary that c=b and there for : EQU 37

$$P_a - P_b = Y \ell n \frac{r_b}{r_a} \tag{37}$$

This relation for internal and external tube will be simplified as fallow. In terms of external tube, it is $P_b=0$ and $P_a=P_{contact}$ and inner and outer radiuses of external tube in corners are regarded r_{oa} and r_{ob} respectively, so according to equation 37 will have: EQU38

$$P_{cont} = Y_o \ell n \frac{r_{ob}}{r_{oa}}$$
(38)

For internal tube it is $P_b=P_{contact}$ and $P_a=P_{imax}$ and inner and outer radius of internal tube in corners are regarded as r_{ia} and r_{ib} respectively, so according to equation 37 will have: EQU39

$$P_{i\max} - P_{cont} = Y_i \ell n \frac{r_{ib}}{r_{ia}}$$
(39)

By merging equations 37 and 38 it is achieved: EQU 40

$$P_{i\max} = Y_i \ell n \frac{Y_{ib}}{r_{ia}} + Y_o \ell n \frac{Y_{ob}}{r_{oa}}$$
(40)

In the above equations, P_{imax} is the maximum internal pressure or calibration pressure that is needed for forming the edges of tube. Y_i , Y_o are flowing stress related to inner and outer tubes respectively.

By considering Von-Miases criteria instead of Terska the equation 37 will become as fallow: EQU41

$$P_a - P_b = K \left[Y \ell n \frac{r_b}{r_a} \right]$$
(41)

According to equation 31 K= $2/\sqrt{3}$ and finally $P_{i max}$ will be: EQU 42

$$P_{i\max} = \frac{2}{\sqrt{3}} \left[Y_i \ell n \frac{r_{ib}}{r_{ia}} + Y_o \ell n \frac{r_{ob}}{r_{oa}} \right]$$
(42)

By comparison the equations 40 & 42 we consider that calibration pressure achieved from Terska criteria is less than one achieved from Von-Maises that because Terska is more cautious than Von-Maises.

Maximum internal pressure $P_{i max}$ is a function of flowing stress and usually the ultimate tension strength of material σ_{UTS} is used instead of Y in this function.

If the final outer radius in the edge is R and the inner one is $r=R-t_0$, the equations 40 & 42 will be as fallow: EQU 43 & 44

$$P_{i\max} = \left[\sigma_{UTS_i} \ell n \frac{R_i}{R_i - t_{i0}} + \sigma_{UTS_o} \times \ell n \frac{R_o}{R_o - t_{o0}}\right]$$
(43)

$$P_{i\max} = \frac{2}{\sqrt{3}} \begin{bmatrix} \sigma_{UTS\,i} \ell n \frac{R_i}{R_i - t_{i0}} + \sigma_{UTS\,o} \times \\ \ell n \frac{R_O}{R_O - t_{o0}} \end{bmatrix}$$
(44)

Determine the loading path of pressure:

The loading path can determine by finding 4 amount of pressure included: sealing pressure, elastic pressure, bursting pressure and calibration pressure respectively.

Yielding pressure is achieved by simplicities the equation 17 for a simple tube with 2 fixed end as fallow: EQU 45

$$P_{iy} = \sigma_{iy} \frac{2t_{i0}}{D_{i0} - t_{i0}} + \sigma_{oy} \frac{2t_{o0}}{D_{o0} - t_{o0}}$$
(45)

Which D_{io} an t_i are the outer diameter and initial thickness of tube and D_{o0} and t_o are the ones of external tube. Bursting pressure is calculated similar to equation 45, of course the ultimate tension strength is used in it. EQU 46

$$P_{ib} = \sigma_{utsi} \frac{2t_{i0}}{D_{i0} - t_{i0}} + \sigma_{utso} \frac{2t_{o0}}{D_{o0} - t_{o0}}$$
(46)

By considering the equations 14, 45, 46 and 44 the loading path will be drawn as fallow: Figure 7





Introduction of studied system:

In order to verify the derived equations the hydro forming process of bi-layer tube was performed experimentally by a hydro forming test unit. In this experimentally study chooses for materials of tubes are based on above considerations and market facilities. We chose a coppery tube according to standard ASTM C 11000 with 99.9 purity percent for external layer and a tube of aluminum according to standard ASTM AA 1050 A with 99.5 purity percent for internal layer.

At first we put the aluminum tube in the coppery one with sufficient gap and then this bi-layer tube is putted in to the die that the needed shape is machined on it, as shown in figure8



Fig. 8

In order to manufacturing the punch and matrix of deep drawing process and the power full cutting dies, Steel 1.2080 named S.P.K is used and also for hydraulic punch and guide rods of die Steel 1.6580 named VCN200 is used.

In the first step, the hydraulic paunch touch the both ends of bi-layer tube and then hydraulic oil will be pumped through the paunch in to specimen according to shown loading path in figure 9.



By performing pressure to the inner tube, firstly both tubes will be fixed together and make a uniform tube and in the next step by increasing the pressure moderately, tube will be extended in to the die cavity and take it shape.

The results:

The forming of the part when is completed that the radius of edge receive the final amount. Various paths are performed in order to optimizing the processes of forming the edges. As shown in shape 10 the radius of edges of both tubes before arriving to the calibration pressure (610.7 bar) have a decreasing trend and after that they remain constant. In shape 11, the complete view and cut view of a hydro formed bi-layer tube which is produced according to loading path in shape 10 is shown.





Conclusion

In this study by extending the governing equations of single-layer tube, the equation related to bi-layer tubes were derived. Using the theoretical pressures that are achieved from mentioned equations show that they can estimate the behavior of bi-layer tubes sufficiently during hydro forming processes.

REFERENCES

- [1] Singh, Harjinder., Fundamentals of Hydroforming, Society of Manufacturing Engineers, 2003.
- [2]- Ahmetoglu, M., Altan, T. "Tube hydroforming: state-of-the-art and future trends," Journal of Materials Processing Technology, Vol. 98, pp 25-33, 2000
- [3]-Asnafi, N., "Analytical modeling of tube hydroforming," Thin-Walled Structure, Vol. 34, pp 295-330, 1999
- [4] Islam M. D., and Olabi, A. G., and Hashmi, M.S., "Feasibility of multi-layered tubular components forming by hydro forming and finite element simulation," Journal of Materials Processing Technology, Vol. 174, pp. 394–398, 2006
- [5] Koc, M., Altan, T., "Prediction of forming limits and parameters in the tube hydroforming process," International Journal of Machine Tools Manufacture, Vol. 42, pp. 123–138, 2002
- [6] Asnafi, N., Skogsgardh, A., "Theoretical and experimental analysis of stroke-controlled tube hydroforming," material science and engineering, Vol 279, pp. 95-100, 2000
- [7] Shigley, J. E., Mechanical engineering design, McGraw Hill. 1986.