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Limit Strains Comparison during Tube and Sheet Hydroforming and Sheet Stamping Processes by Numerical Simulation

C. Nikhare[1] and K. Narasimhan[2]

Abstract: Hydroforming is a manufacturing process that uses a fluid medium to form a component by using high internal pressure. Tube and sheet hydroforming has gained increasing interest in the automotive and aerospace industries because of its many advantages such as part consolidation, good quality of the formed parts etc. The main advantage is that the uniform pressure can be transferred to every where at the same time. Forming limit is the limit of the component up to that extent it can be formed safely. While analyzing hydroforming process, it is often assumed that the limit strains are identical as that of stamped sheet metal of equivalent material properties. It is not clear if such an assumption is valid. In this paper the forming limit strains during hydroforming is predicted. A series of tube bulge tests for tube hydroforming and limiting dome height test for sheet hydroforming and sheet stamping processes are simulated by a commercial finite element solver to predict the limit strains. Numerical simulation of forming limit strains in tube hydroforming with different internal pressure and different simulation set up with or without axial feeding, while in sheet hydroforming and sheet stamping, by changing the specimen geometry are considered to develop wide range of strain paths in the present work. The effects of process conditions on the forming limit strains are detailed. The comparison of limits strains during hydroforming and stamping processes is presented. Prediction of limits strains is based on a novel thickness based necking criterion.

Keyword: Hydroforming, limit strains.

[1] Department of Metallurgical Engineering & Materials Science, IIT BOMBAY, Powai, Mumbai 400 076, INDIA.
[2] corresponding author. email: nara@iitb.ac.in

1 Introduction

The need for reduction of the weight is an important issue in the sheet metal forming industry. Owing to a growing worldwide competitive market, manufacturers are striving to reduce production costs. As a consequence, engineered products are the result of an optimization involving structural design, material selection and manufacturing methods. This involves approaches from different engineering disciplines. Therefore, lightweight construction can be defined as an integrative development technique using all available means from the field of design, material science, and manufacturing in a combined way to reduce the mass of a whole structure and its single elements while at the same time improving the functional quality [Kleiner, Geiger and Klaus (2003)].

In order to reduce the weight of the component, the material has to form to a greater depth of draw i.e. up to maximum limit strains. In many hydroforming process analyses, identical forming limit strains as that of conventional stamping process are assumed. It is not clear if such an assumption is valid. In this paper, forming limit strains during hydroforming are predicted and compared with that of limit strains during conventional stamping.

The hydroforming process has become an effective manufacturing process, because it can be adapted to the manufacturing of complex structural components into a single body with high structural stiffness. Tube hydroforming has been successfully developed in industry such as in the manufacturing of the components of automotive vehicles [Kim, Yang and Han (2004)]. Steel tube has excellent strength to weight ratio and therefore its applications can effectively reduce vehicle weight and improve vehicle stiffness. Other potential advantages are improved dimensional con-

Table 1: Material properties assumed for simulations

n	K (MPa)	Y_s (MPa)	R_0	R_{45}	$R90$	Young's Modulus (GPa)	Poisson's Ratio	Thickness (mm)
0.238	645	211	1.09	0.79	1.29	206	0.33	1.4

trol and reduced cost, both of which are partially due to part consolidation and a large reduction in the welding of stampings to create closed sections [Chen, Soldaat and Moses (2004)].

Sheet metal hydroforming is similar to the stamping process. In the light of the different functions of the liquid, sheet hydroforming can be divided into two categories: active sheet hydroforming and passive sheet hydroforming [Lang, Wang, Kang, Yuan, Zhang, Danckert and Nielsen (2004)]. The tools used for stamping are a die, a punch and blank holder (binder, draw ring). During most of the forming stroke, one side of the sheet is exposed to the fluid or a rubber membrane or diaphragm. Generally, this produces higher and more uniform strain distribution over the entire sheet surface [Singh (2003)]. Using sheet metal hydroforming, greater depth of draw (up to 1.5 times) is possible compared with existing draw-die operations. Due to the application of sealing the sheet hydroformed part has less thinning than the tube hydroformed part and limiting draw ratio can be remarkably improved [Zhang, Zhou, Wang and Xu (2003)].

The full exploitation of hydroforming requires improved understanding of forming limits during hydroforming process. In this paper, the forming limit strains during tube and sheet hydroforming are predicted and compared with that of conventional stamping of equivalent sheet metal quality.

2 Material and Methodology

2.1 Material

Pertinent properties of the deep drawing quality steel considered for the present work is shown in Tab. 1.

2.2 Methodology

The methodology adopted in the simulation of tube hydroforming is tube bulge test and limiting dome height test for sheet hydroforming and sheet stamping process.

2.2.1 Tube Bulge Test

In order to evaluate the forming limit strains during tube hydroforming, the tube bulge test is simulated. These tests use the internal hydraulic pressure to bulge the tube that is supported between a lower and an upper die. The lower part of the die is fixed in movement, while the other is free to move. The two punches in the axial direction of the tube provide for axial feeding [Song, Kim, Kim and Kang (2005), Kim, Kim, Song and Kang (2005), Kim, Kang, Hwang and Park (2004) and Kim, Kim, Song and Kang (2004)]. The following three boundary conditions help to achieve different strain paths: 1) fixed expansion 2) free expansion and 3) axial feed expansion of tubes with different aspect ratios. High internal pressures under relatively low axial feeding will be required to observe the bursting failure. All list conditions will be simulated using FE based code. A novel thickness gradient based criterion is used for predicting the limit strains in the simulation.

2.2.1.1 Fixed expansion of tubes

In fixed tube expansion, the tube is fixed between the two dies (i.e. Die1 and Die2) by giving the coefficient of friction between the tube and dies as 0.5, Fig. 1. When the hydraulic pressure builds up in the tube, it expands in the middle portion without any material feed-in. This operation is completely a stretching operation. This test is performed for different aspect ratios (i.e. expansion zone/tube diameter [l/d ratio = 1 to 1.8]).

2.2.1.2 Free expansion of tubes

In this case, the tube is free to move in the dies (i.e. Die1 and Die2). The coefficient of friction between the tube and the die is assumed as 0.12. This test is performed without and with the middle die portion as shown in Fig. 2 and Fig. 3. When the hydraulic pressure builds up in the tube, the tube expands in the middle portion with material fed in due to force exerted by internal pressure. This test is also performed for different aspect ratios (i.e. l/d ratio = 1 to 1.8).

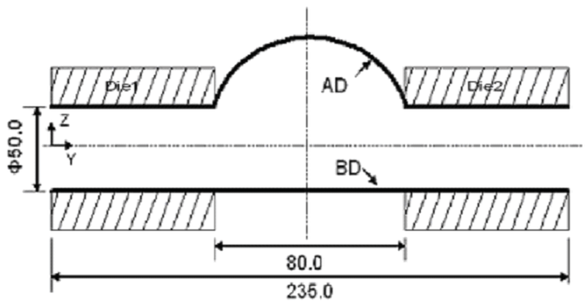

Figure 1: Fixed tube expansion in Hydroforming. BD – Before Deformation AD – After Deformation

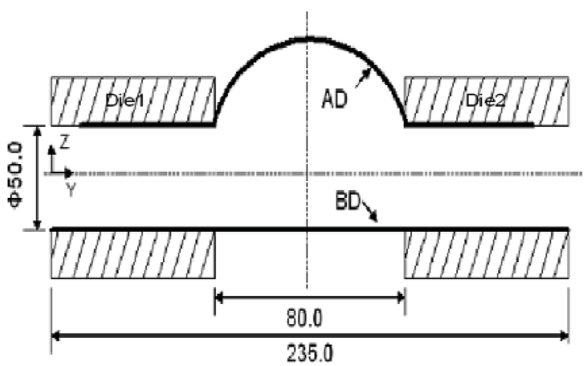

Figure 2: Free tube expansion in hydroforming without middle portion of die

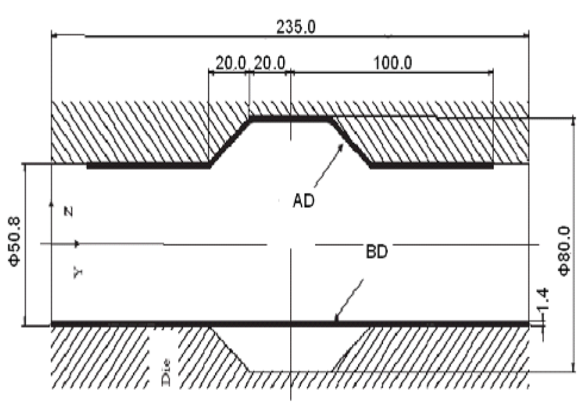

Figure 3: Free tube expansion in hydroforming with middle portion of die

2.2.1.3 Axial feed expansion of tubes

In axial feed expansion of tubes, the tube is simulated for simultaneous application of internal pressures and axial forces from both ends of tubes. The coefficient of friction between the tube and dies is assumed as 0.12. This test is performed without and with the middle dies portion as shown in Fig. 2 and Fig. 3. In this case, additional material feed is provided by two punches at the end of the tubes [Kulkarni, Biswas, Narasimhan, Luo, Mishra, Stoughton and Sachdev (2004)]. When the hydraulic pressure builds up in the tube, the tube expands in the middle portion with material fed in due to axial forces of punch1 and punch2. This test is also performed for different aspect ratio (i.e. l/d ratio = 1 to 1.8).

2.2.2 Limiting dome height test

The Limit Dome Height (LDH) test can be used to obtain various strain conditions by changing the specimen geometry in case of sheet stamping and sheet hydroforming processes. To evaluate the forming limit strain in stamping and hydroforming processes, LDH test is simulated in this work. In LDH test, a hemispherical punch is used as shown in Fig. 4. This minimum cup height is called as the Limiting Dome Height and is used as a measure of formability [Narasimhan, Miles and Wagoner (1995)]. This test will be simulated for predicting forming limit strains using the thickness gradient criterion [Kumar, Date and Narasimhan (1994) and Nandedkar (2000)].

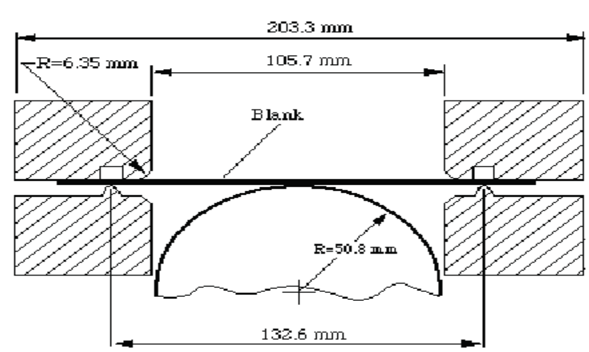

Figure 4: Limiting Dome Height setup for sheet hydroforming and sheet stamping simulation

2.2.3 Numerical simulation

The tube is assumed to be a circular cylinder for purpose of simulation. Variations of wall thickness and material property parameters around the circumference of the tube are neglected. The wall thickness of the tube is taken to be the average measured value of 1.4 mm. Similar relevant assumptions are used in sheet stamping and sheet hydroforming processes. The stress strain curve used according to flow equation, $\sigma = K\varepsilon^n$.

Forming is simulated by using the FE based code PAM-STAMP2G 2004. Tube ends are free to move in the y-direction. The tube is allowed for radial expansion. Internal pressure and axial forces are applied simultaneously and proportionally. The calculated results, for all end conditions considered, are symmetrical to the mid-section of the tube. These symmetry results give added confidence in the accuracy of the numerical calculations obtained from the full model.

2.2.4 Thickness gradient criterion

To predict the forming limit strains coming from the simulation this work will follow the Thickness gradient criterion. During sheet metal forming a localized neck is perceived by the presence of a critical local thickness gradient in the sheet. Such a perception of the neck is independent of the strain path, rate of forming and the type of sheet metal (i.e. the material properties) being formed. The critical local thickness gradient R_{cri}, exists at the on – set of a visible local neck. After start of deformation, a thickness gradient, "$R_{\text{thickness gradient}}$" develops in the deforming sheet which is expressed in Eq. 1.

$$R_{\text{thickness gradient}} = \frac{\text{current thickness of necking element}}{\text{current thickness of neighboring element}} \quad (1)$$

As the deformation progresses, this thickness gradient keeps on reducing from initial value of 1.0. The thickness gradient becomes steeper at the on – set of localized necking and at this transition from diffused necking it attains a critical value. The criterion is represented in Eq. 2.

$$R_{\text{thickness gradient}} \leq R_{\text{cri}} \quad (2)$$

The R_{cri} is experimentally estimated as 0.92. If $R_{\text{thickness gradient}}$ is less than 0.92, the component is considered as necked [Kumar, Date and Narasimhan (1994) and Nandedkar (2000)].

3 Results and Discussion

Fig. 5 compares the input-output pressure curve obtained from FEA simulation. The sudden drop of output pressure is an indication of excessive thinning in the expansion region. The axial displacement vs. time applied during axial feed expansion of tubes is shown in Fig. 6.

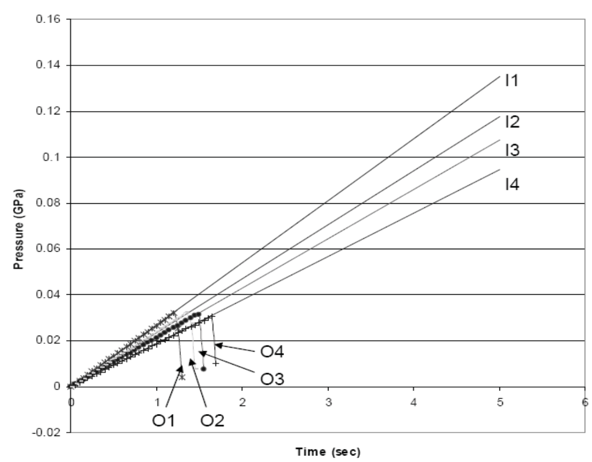

Figure 5: Input-Output pressure-time histories during hydroforming

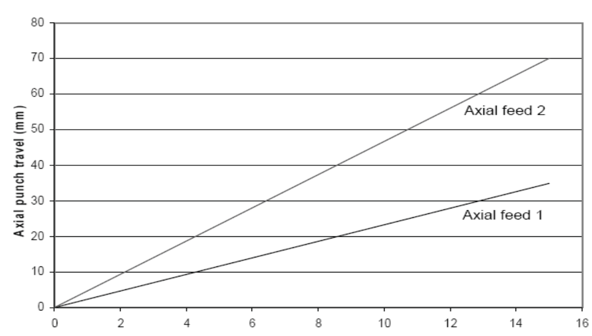

Figure 6: Axial punch displacement during axial feed hydroforming

In fixed expansion of tubes, when we reduce the aspect ratio and fix the pressure curve for different simulation, both the strains is increasing but with the combination of increase of pressure curves and fixed aspect ratio, the strains are decreasing. The axial stress and circumferential stress are generated simultaneously because the tube is not allowed to feed in the expansion zone. Thus strain develops in stretching domain.

In free expansion of tubes, as soon as we reduce the aspect ratio the strains are increasing but the value of strains are more. As the dominant stress here is circumferential stress and also the tube is free to feed in, the value of strains are more than in fixed expansion of tubes, but the percentage change of the major strain is less than the minor strain when compared with fixed expansion of tubes. When the aspect ratio is fixed and the pressure curves increased, the tube is self fed in as per the force generated by the fluid pressure on the tube material. So in this case the circumferential stress dominates the axial stress, so that is why the percentage change of major strain is less than minor strain when compared with fixed expansion of tubes. Here the strain path leads towards plane strain conditions.

In axial feed expansion of tubes, for different aspect ratio, the strains decrease in same manner as in fixed expansion of tubes and free expansion. So, for various combinations of axial feed and internal pressure curves we obtain limit strains in stretching, in plane strain and mostly in drawing zone when the die support is used.

Fig. 7 shows the results of excessive pressurizing during the bulging process, necking occurs at the middle of the tube wall as per the thickness gradient criterion. The picking of neck point at a particular time by thickness gradient criterion is the same at which the output internal pressure of tubes drops as per the Fig. 5, confirming the onset of neck.

Fig. 8 shows how the thickness gradient is developed with respect to time from case I1 to I4. It also shows that the necking pressure is continuously decreasing from I1 to I4, is the matter of fact of optimization for a particular combination of process conditions and the material properties.

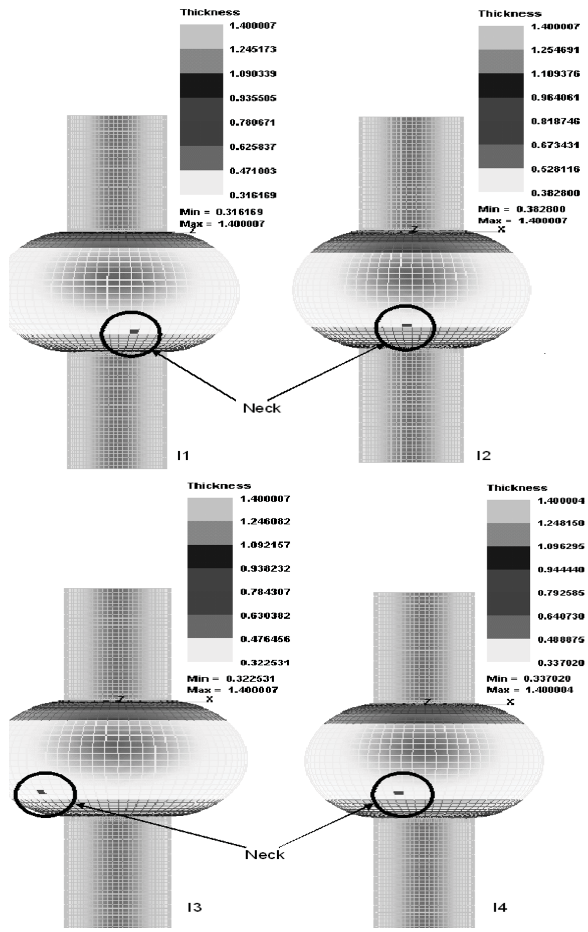

Figure 7: Simulation necked tubes obtained from bulge test under different loading paths

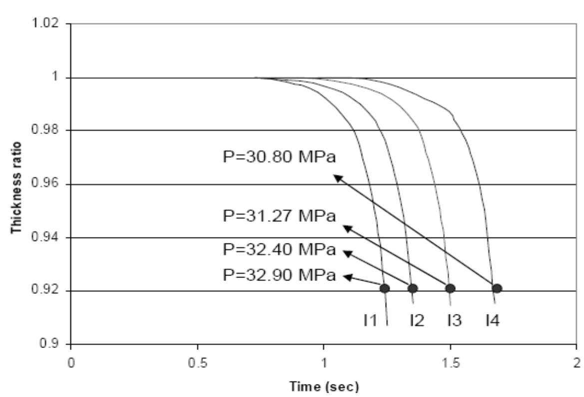

Figure 8: Thickness ratio along time during tube hydroforming under different loading paths

Tab. 2 presents the strain conditions defined for the various tube hydroforming simulations.

Table 2: Details of different simulations during tube hydroforming. FA – Axial feed expansion, FR - Free expansion, FI – Fixed expansion

Sr. No	Boundary Conditions	Emaj	Emin	Emin/Emaj
1	FA	0.8356	-0.2206	-0.2640
2	FA	0.7030	-0.1672	-0.2378
3	FA	0.6820	-0.1588	-0.2328
4	FA	0.5472	-0.1083	-0.1979
5	FA	0.4385	-0.0170	-0.0387
6	FA	0.3739	0.0410	0.1096
7	FA	0.3583	0.0609	0.1699
8	FA	0.3363	0.0803	0.2387
9	FR	0.3390	0.1080	0.3185
10	FR	0.3901	0.1870	0.4793
11	FI	0.4877	0.2644	0.5421
12	FI	0.5282	0.3018	0.5713
13	FI	0.6760	0.4139	0.6122
14	FI	0.7117	0.4330	0.6084
15	FI	0.8257	0.5188	0.6283
16	FI	0.8980	0.5748	0.6400

During sheet hydroforming, a wide range of strain paths are developed by changing the specimen geometry (i.e. changing sheet width with length constant). The sheet with length constant of 200mm and the width is changing from 25mm with an increment of 25mm up to the total width of 200mm. The simulation for different blank width is possible, because the fluid is with respect to blank, so what may be the blank area; the fluid is only applied to that. But this is not the case with experiments. To get the wide range of strain paths during experiments is the point of discussion.

Tab. 3 presents the strain conditions defined for the various sheet hydroforming simulations.

Thus in this way a wide range of limit strains from drawing to complete stretching is obtained. Fig. 9 shows the comparison of limit strains during hydroforming and sheet stamping process. The graph clearly shows that the limit strains in tube hydroforming are higher than that in sheet hydroforming and the limit strains in sheet hydroforming are higher than that in sheet stamping process. The difference of limit strains in tube hydroforming and sheet hydroforming is because no solid

Table 3: Details of different simulations during sheet hydroforming

Sr. No.	Emaj	Emin	Emin/Emaj
1	0.4477	-0.2242	-0.5000
2	0.5301	-0.2406	-0.4538
3	0.3010	-0.08	-0.2650
4	0.2850	0.089	0.3120
5	0.2999	0.1236	0.4133
6	0.5643	0.278	0.4920
7	0.5000	0.256	0.5120

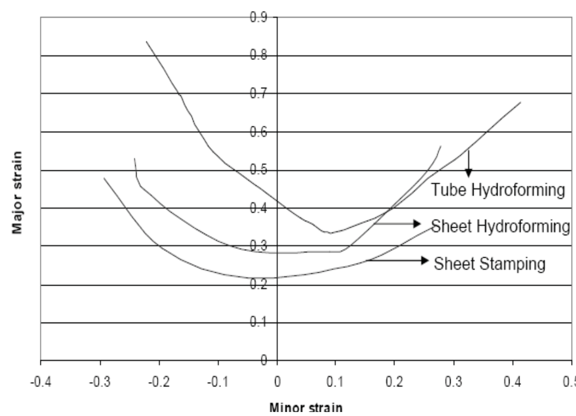

Figure 9: Forming limit curve during hydroforming and stamping processes

tool is used in the expansion zone during tube hydroforming but in sheet hydroforming the punch is completely in contact with the sheet (i.e. from wall to bottom) that may be called as friction effect. The limit strains difference in drawing is higher than in stretching when compare tube and sheet hydroforming is because the material is fed-in in case of drawing and due to which no excessive thinning is developed than in stretching before necking.

The difference in limit strain between sheet hydroforming and sheet stamping is because the tool is not completely in contact with the sheet in later case and because of that the necking occurs particularly in the walls before goes to as much thinning as in the prior case. Fig. 10 and Fig. 11 shows the thickness strain distribution and thickness ratio distribution along the length of sheet for 28.50mm cup height. It clearly shows that the thickness strain is more uniformly distributed in case of sheet hydroforming than that in sheet stamping which is verification for forming limit curve. Also the necking for sheet hydroforming is delayed than for sheet stamping process. Therefore, it appears that effectively more useful forming could be achieved in hydroforming compared to stamping operations.

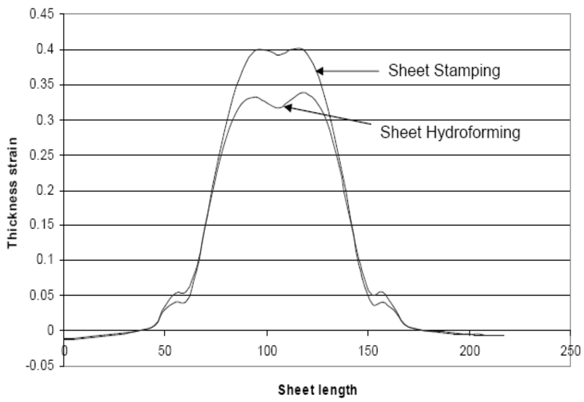

Figure 10: Thickness strain distribution along the length of sheet for a 28.50mm cup height

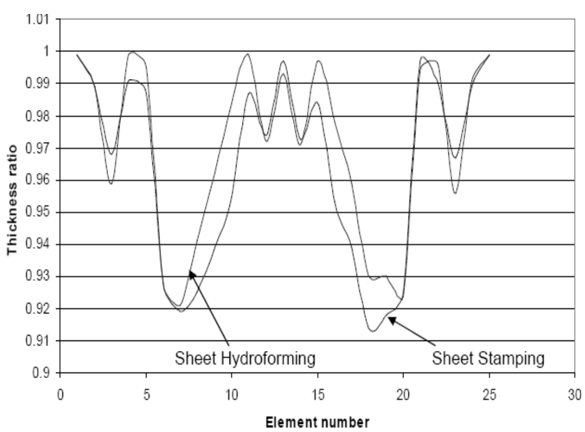

Figure 11: Thickness ratio distribution along the length of sheet for a 28.50mm cup height

4 Conclusions

In order to evaluate the forming limit strains during hydroforming process, simulation under various combinations of internal pressure and axial loading and different process conditions were studied in this paper. Using thickness gradient criterion, the occurrence of necking i.e. forming limit strains of tube hydroforming and of sheet during sheet hydroforming and sheet stamping processes were estimated. Comparison of forming limit strains during hydroforming process and sheet stamping process shows that the limit strains during hydroforming are marginally higher than that of sheet stamping process.

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