Hydroformability study of seamless tube using Gurson-Tvergaard-Needleman (GTN) fracture model

K R Harisankar1, A Omar1 and K Narasimhan1

1Department of Metallurgical Engineering and Materials Science, Indian Institute of Technology Bombay
E-mail: nara@iitb.ac.in

Abstract. Tube hydroforming process is an advanced manufacturing process in which tube acting as blank is placed in between the dies and deformed with the help of hydraulic pressure. It has several advantages over conventional stamping process such as high strength to weight ratio, higher reliability, less tooling cost etc. Fracture surface investigation of tube hydroformed samples reveal dimple formation in the form of void coalescence which is a characteristic feature of ductile fracture. Hence, in order to accurately predict the limiting strains at fracture it is important to model the process using ductile damage criteria. Fracture criteria are broadly classified into two, microscopic and macroscopic. In the present work Gurson-Tvergaard-Needleman (GTN) model, which is a microscopic based ductile damage criteria, was used for predicting the limiting strains at fracture for seamless steel tubes and implemented in explicit finite element software, ABAQUS, for variety of strain path and boundary conditions to obtain fracture based forming limit diagram. The original void porosity, the critical porosity and fracture porosity of the Gurson-Tvergaard-Needleman model were determined by image analysis of scanning electron micrographs of the specimen at different testing conditions of the uniaxial tensile test. The other parameters of the model were determined by using inverse approach combined with uniaxial tensile test and simulation. Predicted FLD is found to be in good agreement with the experimental FLD. Furthermore, numerical simulation based parametric study was carried out to understand the impact of various GTN parameters on different aspects of formability parameters such as bursting pressure, bulge height, principal strains and strain path to develop the understanding of deformation and fracture behaviour at the micro-level during tube hydroforming process.

Keywords: Tube hydroforming, FLD, GTN model, FEM, Porosity.

1. Introduction

The tube hydroforming is an advanced manufacturing process, widely used in automotive and aerospace industries to form complex parts with higher strength to weight ratio. Hydroforming process involves part consolidation leading to great benefits to various industries in the manufacturing sectors by reducing their long term expenditure [1]. In this process, a tube is formed into the shape of the die cavity by simultaneously applying internal pressure and axial feeding of the tube material to the critical forming zone [2]. Thus it is of prime importance to assess the hydroformability of a tube material for a defect free product. Hydroformability can be assessed in many ways, such as corner filling, maximum bulge height, forming limit diagrams (FLD) and minimum thickness variation amongst which FLD is one of
the most widely used tool to assess the materials formability and was first proposed by Keeler, Backofen and Goodwin in 1960's [3]. It is a plot of major principal strain (plotted on abscissa) and minor principal strains (plotted on ordinate) at onset of neck or fracture. The strain space below the FLC during the deformation is regarded as the safe region for a given forming process. Although the application of the FLD for tube hydroforming remains the same as that of the sheet metal forming process [4], the development or obtaining of FLC differs greatly with stamping and tube hydroforming process.

In stamping process, different stress states are generated and thus different strain paths can be obtained by varying the geometry of the specimen used whereas in hydroforming the same can be obtained by the combination of geometrical factors such as bulging zone length termed as L/D ratio as well as tube length or feeding length along with process parameters (i.e. loading path) and tooling boundary condition such as axial or end feeding, free bulging without axial feeding and fixed or end constraint. Hwang et al. proposed an experimental technique to obtain the strain paths on the right side of the FLD by fixed bulge test [5]. Davies et al. used axial feeding condition to produce strain paths on the left hand side of the FLD [6]. The different strain ratios were obtained by varying the loading path. Several researchers proposed different method to predict FLD based on fracture and necking criteria. Hashemi et al. predicted localized strain and stress based FLD for DP-600 steel using Marciniak and Kuczynski (M-K) criterion [7]. Omar et al. used thickness gradient based criterion for obtaining FLD of electric resistant welded drawing quality (DQ) steel [8]. The basic assumption behind the necking Criteria is that localized necking occurs due to the plastic instability.

A macroscopic approach to predict the FLD by considering the micro voids/cracks nucleation, growth and coalescence in a ductile material based on continuum damage mechanics is extensively used [9]. Zhang et al. investigated the fracture and the effect of friction in the corner filling behavior of AA 5052 aluminum alloy in hydroforming process based on the GTN ductile damage model [10]. Teng et al. predicted the bursting behavior in tube hydroforming of 5A02 aluminum alloy using the GTN model in ABAQUS software [11]. Butcher et al. investigated the effect of axial feed on formability and damage development in tube hydroforming of DP 600 steel based on the GTN damage model in LS-DYNA software [12]. Bu-gang et al. investigated the bursting behavior of a stainless steel T-shape hydroforming based on the GTN model [13]. Oyane’s ductile damage criterion was used by several researchers such as Kim et al. [14] to predict the FLD of SKTM-11A and Lei et al. [15] predicted the bursting behavior of SPCC tube hydroforming.

In this work, the experimental measurement and prediction of FLD in straight tube hydroforming of a seamless medium carbon steel tubes is presented. The prediction is carried out based on the GTN ductile damage model in ABAQUS software and the GTN parameters were identified through experiments and inverse approach. The challenging task with GTN model is the accurate determination of its parameters which are usually identified through experiments and inverse approach. It has been seen that slight variation in GTN parameters can affect the forming characteristics and fracture prediction of the tube. Therefore additionally, a parametric study of GTN parameters was conducted to investigate the effect of each parameter on the hydroformability like bulge height, bursting pressure and strain path to determine the extent of impact of initial void porosity as well as its microscopic development such as nucleation and growth has on formability.

2. Gurson-Tvergaard-Needleman (GTN) ductile damage model

The Gurson-Tvergaard-Needleman damage model based on micro cracks/voids nucleation, growth and coalescence has been widely used to predict the ductile fractures. Gurson (1977) was the first to develop the model based on the homogeneity theory for the spherical voids and this model tends to overestimate the material formability. Tvergaard (1981) introduced calibration parameters into the model: \( q_1 \approx 1 - 1.5, q_2 \approx 1 \) and \( q_3 = q_1^2 \). These parameters were obtained by conducting experiments on wide range of steel and Aluminum samples and found to be in the range quoted above. Later on Tvergaard and Needleman (1984) modified the model with damage parameter, \( f^* \) to account for the coalescence of voids [16].
GTN yield criterion is written as

$$
\Phi = \left( \frac{\bar{\sigma}}{\sigma_y} \right)^2 + 2q_1 f^* \cosh \left( -q_2 \frac{\sigma_m}{2\sigma_y} \right) - \left( 1 + q_3 f^{*2} \right) = 0 \tag{1}
$$

Where, $\bar{\sigma}$ is the Von-Mises equivalent stress, $\sigma_i$ is the equivalent tensile flow stress and $\sigma_m$ is the hydrostatic stress. The damage parameter $f^*$ is defined in terms of void fraction as

$$
f^* = \begin{cases} 
 f & \text{if } f \leq f_c \\
 f_c + \frac{f_f-f_c}{f_f-f_c} (f-f_c) & \text{if } f_c < f < f_F \\
 f_F & \text{if } f \geq f_F 
\end{cases} \tag{2}
$$

Where, $f_c = \left( q_1 + \sqrt{q_1^2-q_3} \right)$, $f$ is the void volume fraction (vff), $f_c$ critical value of void volume fraction at onset of void coalescence, $f_F$ is fracture void volume fraction and these parameter are known as coalescence parameters.

The growth rate of void volume fraction is the sum of growth rate of existing voids ($\dot{f}_g$) and nucleation rate of new voids ($\dot{f}_n$) as follows

$$
\dot{f} = \dot{f}_g + \dot{f}_n \tag{3}
$$

The initial state is the initial void volume fraction, $f_0$. The growth rate of existing voids is proportional to hydrostatic plastic strain rate as follows

$$
\dot{f}_g = (1-f) \dot{\epsilon}_{kk}^p \tag{4}
$$

The nucleation rate of new voids is expressed to be plastic strain controlled and nucleation rate as follows

$$
\dot{f}_n = \frac{f_N}{S_N \sqrt{2\pi}} \exp \left( -\frac{1}{2} \left( \frac{\bar{\sigma}^p - \epsilon_N}{S_N} \right)^2 \right) \dot{\epsilon}^p \tag{5}
$$

Where, $f_N$ is volume fraction of nucleating particles, $\epsilon_N$ is mean strain for void nucleation, $S_N$ is standard deviation of mean strain for void nucleation, $\bar{\sigma}^p$ is Von-Mises plastic strain and $\dot{\epsilon}^p$ is Von-Mises plastic strain rate respectively. The $f_N$, $\epsilon_N$ and $S_N$ are known as nucleation parameters.

### 3. Material Details

The tube material used for this study is ASTM A106-B seamless tube of 48.4 mm diameter and 3.68 mm thickness. The chemical composition of the tube is given in table 1. Tensile specimens were cut from the tube in longitudinal direction to determine the mechanical properties and are presented in table 2. Figure 1 shows the engineering stress-strain and true stress-strain curve for the tested material.

| Element | C | Mn | P | S | Si | Cr | Co | Mo | Ni |
|---------|---|----|---|---|----|----|----|----|----|
| Composition (%) | 0.3 | 0.5 | 0.035 | 0.035 | 0.1 | 0.4 | 0.4 | 0.15 | 0.4 |

| Yield strength (MPa) | Tensile strength (MPa) | Strain hardening Exponent ‘n’ | Strength coefficient ‘K’ (MPa) |
|----------------------|------------------------|-----------------------------|-----------------------------|
| 405                  | 516                    | 0.21                        | 869                         |
4. Experimental methodology

The tube bulge test was performed on a 200 ton hydroforming machine. The details of the machine are described elsewhere [8]. In order to produce different deformation modes, experiments were carried out in three boundary conditions. The axial feed expansion bulge test to produce strain paths in the drawing side of the FLD, fixed expansion condition to produce strain paths in the stretching side of the FLD and free expansion condition to produce strain paths near to plane strain condition. Apart from that, two $L/D$ ratios 1 and 3 were used to produce variety of strain paths. Since the diameter of the tubes are 48.4 mm so the resulting bulging length $L'$ for $L/D = 1$ and 3 will be 48.4 mm and 145.2 mm respectively. The bursting pressure is about 850 to 900 bar (i.e. 85 to 90 MPa). The loading path are chosen in between the two extremes of high feed rate as well as high pressure rate whose purpose is also to develop variety of strain paths. The axial feed mentioned in figure 2 is the combination of both the sides of axial punches. Each of the tube specimens were printed with a circular grid of 2 mm diameter with 3 mm center distance. Principal strains near the fracture of the tube specimens were measured using digital image correlation technique software ARGUS developed by, GOM.

4.1 Identification of Gurson-Tvergaard-Needleman damage model parameters

According to the GTN yield function, a total of 9 parameters were needed to be identified. In the present work, the values of $q_1$, $q_2$ and $q_3$ were assumed to be 1.5, 1 and 2.25 respectively [10, 11, 13, 17]. The values of void volume fraction parameters (coalescence parameters) were identified through image analysis of scanning electron micrographs of undeformed samples ($f_0$), at the onset of neck ($f_c$) and the fracture surface of uniaxial tensile test samples ($f_F$). The scanning electron micrographs of each deformation state is shown in figure 3. For each of the testing conditions, at least 20 images at different locations were analyzed through image analysis software ImageJ and average of them were taken as GTN parameters values and were later used in the simulation.

![Figure 1. Engineering and true stress–strain curves.](image1)

![Figure 2. Loading path for axial feed expansion.](image2)

![Figure 3. SEM images at (a) undeformed, (b) at onset of neck and (c) fracture.](image3)
The values of nucleation parameters were determined by inverse approach, in which the numerical results of the true stress-strain curve of uniaxial tensile test is compared with experimental obtained true stress-strain curve. The finite element model was simulated in Abaqus/Explicit, with C3D8R solid elements. Figure 4 shows the comparison of the stress-strain curve with best-fit for the set of GTN parameters further used as a fracture criterion in numerical prediction and tabulated in table 3.

Figure 4. Comparison of stress-strain curve.

| q₁  | q₂  | q₃  | f₀       | fₜ   | fᵢ   | εₚ   | Sₚ   | fₚ   |
|-----|-----|-----|----------|------|------|------|------|------|
| 1.5 | 1   | 2.25| 0.00011  | 0.0168| 0.0409| 0.3  | 0.1  | 0.022 |

Table 3. GTN parameters.

5. Simulation methodology

The finite element model for the tube bulge tests was developed with the help of Abaqus/Explicit by considering the punch as solid moving body and die as rigid fixed body while the tube was assigned as elastic plastic deformable body. The brick element with reduced integration and hourglass control (C3D8R) was used. Mesh size of 2 mm has being selected after performing the mesh sensitivity analysis as shown in figure 5 and the semi automatic mass scaling with scale to target time increment of 0.001 was used. Figure 6 shows the assembly of the tube hydroforming toolset. In order to simulate the fixed condition, the two ends of the tube were end castled with zero degree of freedom in order to achieve a perfectly fixed condition with no axial flow of material. In other words, the axial length of the tubes remains same and axial compression is zero. Since the experiments were conducted with lubricated die to allow smooth material flow to the bulging region, the nominal value of the coefficient of friction between the die and tube was assumed as 0.04 for axial feed expansion and free condition. In axial feed condition, displacement is given to the two punches which push the tube material to the critical bulging region and henceforth decreasing the necking rate and increasing the formability. The simulations were performed using the same loading paths as in the experiments. The Holloman’s power law \( \sigma = K \varepsilon^n \) is used as the work hardening model and its parameters value are mentioned in table 2.

Figure 5. Mesh sensitivity analysis.

Figure 6. FEM model of tube hydroforming toolset.
6. Results and discussions

6.1 Forming limit diagram

Figure 7 shows the comparison of fractured tube from simulation and experiment. The nearest point to the fracture is the critical point at which the principal strains are calculated. Percentage error in prediction is calculated by the square root of the sum of the square of difference in major principal strain and minor principal strain in experiment and simulations. The limit strains were measured in the vicinity of the fracture and percentage error in prediction is given in the table 4. The forming limit curves were plotted for both simulation and experiment as shown in figure 8.

![Figure 7. Comparison of fracture in prediction with experiment.](image)

| Boundary conditions | Simulation Major principal strain | Simulation Minor principal strain | Experimental Major principal strain | Experimental Minor principal strain | Percentage error in simulation |
|---------------------|-----------------------------------|---------------------------------|-----------------------------------|-----------------------------------|-------------------------------|
| Axial feed L/D = 1  | 0.31                              | -0.17                           | 0.33                              | -0.19                             | 2.828                         |
|                     | 0.37                              | -0.21                           | 0.38                              | -0.20                             | 1.414                         |
|                     | 0.31                              | -0.17                           | 0.30                              | -0.16                             | 1.414                         |
|                     | 0.28                              | -0.11                           | 0.26                              | -0.07                             | 4.472                         |
|                     | 0.29                              | -0.15                           | 0.29                              | -0.16                             | 1.000                         |
| Axial feed L/D = 3  | 0.30                              | -0.13                           | 0.28                              | -0.13                             | 2.000                         |
|                     | 0.32                              | -0.14                           | 0.33                              | -0.14                             | 1.000                         |
| Fixed L/D = 1       | 0.24                              | 0.01                            | 0.21                              | 0.01                              | 3.000                         |
|                     | 0.27                              | 0.04                            | 0.24                              | 0.02                              | 3.606                         |
|                     | 0.26                              | 0.05                            | 0.23                              | 0.02                              | 4.243                         |
| Free L/D = 1        | 0.27                              | -0.03                           | 0.24                              | 0.02                              | 5.831                         |
|                     | 0.24                              | -0.03                           | 0.25                              | -0.02                             | 1.414                         |
| Free L/D = 3        | 0.25                              | -0.03                           | 0.22                              | 0.03                              | 6.708                         |

6.2 A parametric study: Effect of Gurson-Tvergaard-Needleman parameters on hydroformability

The parametric study was conducted in order to assess the effect of each parameter on hydroformability of tube in terms of bulge height, bursting pressure and strain path by varying each parameter within a certain realistic range. The study was performed to assess the effect of microstructural void growth and nucleation on formability parameters and thus simulations were carried out with constant linear loading path and same (L/D = 1) geometrical conditions. Six parameters, namely $f_0$, $f_c$, $f_F$, $\varepsilon_N$, $S_N$ and $f_N$ were considered for this study, the effect of each is mentioned in subsequent section.

6.2.1 Initial void volume fraction ($f_0$). Initial void volume fraction is a measure of pores which remain unoccupied in the material creating non-uniformity and thus being detrimental to mechanical properties
and lifespan of material. As the initial volume fraction increases the bulge height and bursting pressure found to be decreased, whereas the strain path remains unchanged as shown in figure 9(a).

6.2.2 Critical void volume fraction ($f_c$). Critical void volume fraction is corresponding to the void volume fraction at which material starts to lose its load-carrying capacity due to the void coalescence. The high value of critical void volume fraction results in more strain hardening which leads to higher bursting pressure and bulge height, without impacting the strain path as shown in figure 9(b).

![Figure 8. FLD: Comparison between prediction and experimentally measured limit strains.](image)

6.2.3 Final void volume fraction ($f_f$). Final void volume fraction corresponds to the void volume fraction at which material completely loses its load-carrying capacity and is fractured. Final void volume fraction does appear to have much effect on bulge height and bursting pressure, since the load carrying capacity decays very fast in ductile materials. It also does not affect the strain path as shown in figure 9(c).

![Figure 9. Effect of coalescence parameters on strain path (a) initial void volume fraction ($f_0$) (b) critical void volume fraction ($f_c$) (c) final void volume fraction ($f_f$).](image)

6.2.4 Mean strain for void nucleation ($\varepsilon_N$). Mean strain for nucleation is the plastic strain around which new voids are nucleating. If the mean strain for nucleation is high, the hydroformability will be much more because of the lower nucleation rate. The bulge height and bursting pressure found to be increasing as the mean strain for nucleation increases as shown in figure 10(a).

6.2.5 Standard deviation of mean strain for void nucleation ($S_N$). In GTN model, the nucleation is assumed to follow a pattern of normal distribution with plastic strain controlled. Standard deviation of mean strain for nucleation is a measure of dispersion in the plastic strain. If the standard deviation of mean strain for nucleation is more, implies that the nucleation rate is less. The bulge height and bursting pressure found to be increasing as the standard deviation of mean strain for nucleation is increasing and strain path remains unaltered as shown in figure 10(b).

6.2.6 Void volume fraction of new nucleating voids ($f_N$). As the void volume fraction of new nucleating voids increases, nucleation rate of new voids will be higher leading to early fracture. The bulge height and bursting pressure found to be decreasing as the void volume fraction of new nucleating voids increases as shown in figure 10(c). For all the above listed parameters strain path remains unaffected.
7. Conclusion

The experimental work was carried out to construct the FLD for tube hydroforming of seamless carbon steel (ASTM A106B) tube. The FLD was predicted through simulation using commercially available FEM based software Abaqus/Explicit using microscopic based Gurson-Tvergaard-Needleman (GTN) damage model. In order to obtain quantitatively good prediction of limiting strains, identification of GTN model parameters are crucial. Model parameters were identified through inverse approach followed by metallographic study. Experimentally obtained FLD was found to be in agreement with predicted FLD with maximum percentage error of 6.708%. The parametric study reveals that each variable having an effect on hydroformability of the tube, but none of the parameters had any effect on strain path. Thus, strain path is only dependent on the loading path and the different boundary conditions. In coalescence parameters, critical void volume fraction \( f_c \) having the maximum effect on hydroformability. In case of nucleation parameters, standard deviation of mean strain for nucleation, \( S_N \) had the significant effect on hydroformability. Furthermore, the present parametric study reveals that the formability and fracture behaviour is interdependent on multiple combinations of GTN parameters. Moreover a detail study can be performed to assess the interdependency of geometric parameters along with varying material property and geometric conditions as well as loading path to provide the detail qualitative as well as quantitative understanding of the effect various parameters on the fracture behaviour and hydroformability of tube and the same can be compared with stamping process.

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