

Bending Limit Curve for Rotary Draw Bending of Tubular Components in Automotive Hydroforming Applications

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ABSTRACT

One of the most significant manufacturability-criteria of a tubular component in bending and/or hydroforming operation is the formability limit of the selected tube material. Currently the most common tool used to determine the material formability is the North American "standard" forming limit diagram (FLD) developed for low carbon sheet steels.

It was shown, that applying the experimental FLDs developed for high strength steel materials or standard FLC on rotary draw bending process would, however, lead to under-utilization of the tube material. Therefore, on the basis of the elementary theory of bending and introducing the bendforming-related "Displacement of Neutral Axis" as a bend parameter, new relationships were developed for accurate prediction of principal bending strains. Subsequently, the residual strains from tubing process were taken in consideration to determine the exact bendability limit for tubular components in rotary draw bending. The position of so-called Bending Limit Curve "BLC" becomes, beside the wall thickness and the n-value of the tube material, also a function of outside diameter of considered tube.

Series of steel tubes of different materials and geometries were bent with decreasing bend radii until their failure. The results of strain measurements indicate that the principal bending strains were a function of bend-ratio only (therefore material neutral) and show a very good correlation predicted strains. Furthermore, the paper explains the developed bending limit curve and demonstrates the influence of tube's outside diameter on its bendability limit. The high accuracy of the calculated bending strain paths and the applicability of the developed bending limit curve were shown using the experimental data and FEA-simulations.

INTRODUCTION

The tube hydroforming process has proven ability to manufacture high quality parts with superior dimensional accuracy, structural strength, rigidity, repeatability and part consolidation as well as lower production cost in

comparison to conventional stamping and welding processes. Hydroforming utilizes fluid pressure applied to the inside of a tube, forcing the tube wall outwards to the surface of a die cavity representing the desired shape of the hydroformed part. However, manufacturing of tubular parts with complex structures, particularly in the automotive industry, often requires one or more pre-forming operations prior to the actual hydroforming process. CNC mandrel rotary draw bending is the most frequently applied pre-forming operations in the tube hydroforming industry. The purpose of pre-bending is to achieve centerline-geometry close to that of the final part to be manufactured by hydroforming, thereby enabling the tube to fit into the die cavity.

Bendforming influences the properties of tube material and causes non-uniform plastic deformations in bent regions which restrict the tube's hydroformability (1). In special cases such as pressure sequence hydroforming "PSH" developed by Vari-Form (2), the process is limited predominantly by the material's ability to survive the bending process. Thus, understanding material behavior and prediction of strains as well as the forming limits of tubular materials in the bending process becomes more important and crucial.

As stated, applying conventional forming limit diagrams on rotary draw bending process lead very often to under-utilization of tube material (3). This effect is demonstrated in Figure 1, where the measured bending strains are plotted on a conventional Forming Limit Diagram, which has been developed based on mechanical properties of parent material from which the tube was made. As it can be observed, a significant portion of the plotted strains lay above the failure limit curve "FLC". For this case, the standard FLD predicts a definite failure for the tube material. This prediction, however, doesn't take place as the tube survives the bending process without any failure or neck. Hence, this article documents newly developed relations for a more accurate prediction of bend strains and demonstrates the correlation between prediction and the experimentally obtained strain data. It also presents a method of generating Bending Limit Curve "BLC" for rotary draw bending of tubular steel materials.

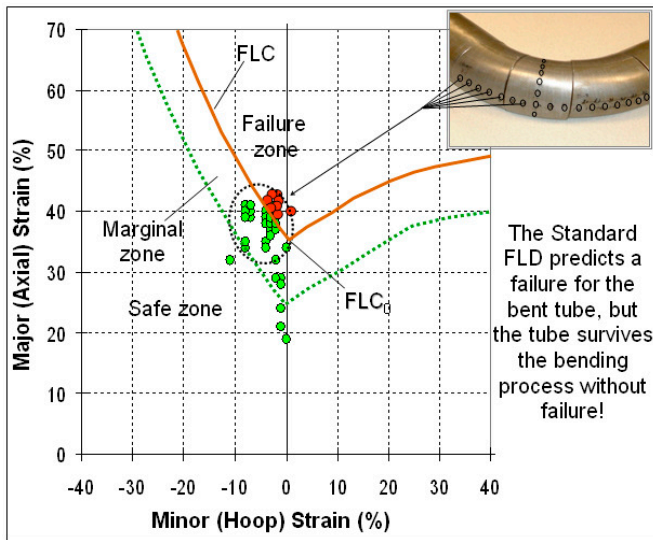


Figure 1: Conventional forming limit diagram (FLD) and the plotted strains measured along the outside of a bent mild steel tube (tube not failed).

MATERIAL BEHAVIOR IN TUBE ROTARY DRAW BENDING

Figure 2 shows the schematic of a conventional mandrel tube rotary draw bender utilizing five major tools (mandrel, pressure die, wiper die, bend die and clamp die) which all interact with one another via the tube during the bending process. In the initial state, the bend die, clamp die and pressure die are all oriented parallel to the tube length axis. Upon sliding the tube into position over the mandrel and closing the clamp die by applying a force/torque on the tube, the bending operation begins while the bend die and the clamp die rotate together pulling the tube over the mandrel.

At the very beginning of the bending process, the deformation of tube remains elastic until the induced compression and tension stresses in the tube material at the inside/outside radius reach their Yield point and the plastic flow begins. By further rotation of the bend die, the plastic deformation in cross-section of tube grows in both radial and axial directions, while its radius decreases gradually until it achieves the centre-line radius " R " of the bend-die. At this angle-position the forming zone is completely developed and the ultimate level of possible plastic deformation in tube cross-section has been achieved. Upon completion of this bending portion, the plastic deformation propagates only along the tube length axis.

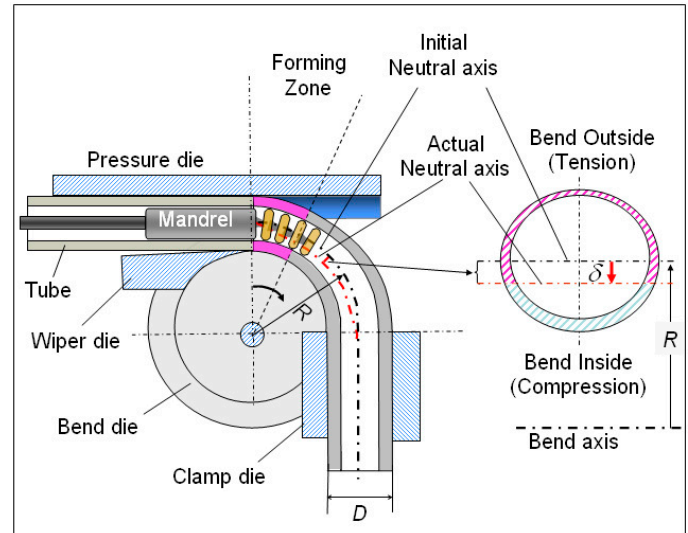


Figure 2: Schematic of a tube mandrel rotary draw bending, indicating the forming zone and the position of initial/actual neutral axis in cross-section of a bent tube.

The thickness increase in inside and its reduction in outside of the bend throughout the bendforming lead to immediate disproportions between the compression and tension areas in cross-section of tube. Therefore, all material layers in the bend area undergo stress and strain conditions which change continuously during bendforming. No layer is continuously strain-free and no layer is continuously stress-free. Due to these interactions, the initial neutral axis experiences an elongation, which in-turn leads to the elongation of tube in the bend region. Consequently, the next layer between the initial neutral axis and tube inside radius becomes the actual strain-neutral axis (Figure 3) obtaining exactly the same geometry characteristics (length and thickness) as the initial neutral axis prior to the bending operation (4, 5). This phenomenon is characterized here as the *displacement of neutral axis* " δ ", representing the distance between the initial and the actual neutral axis. Figure 3 illustrates schematically the effects of the displacement of neutral axis on axial strain distribution in cross-section of a bent tube.

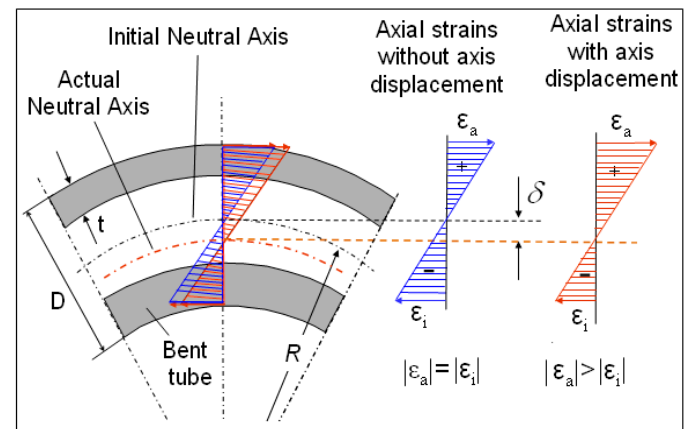


Figure 3: Displacement of neutral axis " δ " and its influence on strain distributions in cross-section of bent tubes.

With “D” as outside diameter of the bent tube and “R” as its centre-line bend radius, the displacement of neutral axis δ can be determined using the Equation 1; (6).

$$\delta \approx 0.25 \cdot D \cdot (D/R) \quad /1/$$

In Equation 1, the term “D/R” referred to as the “bend severity”. Hence, the smaller the bend radius and/or the larger the tube’s outside diameter, the more severe the bend and the higher the displacement. The most common term used in bending industry to describe the severity of a bend is the “Bend-Ratio” or (R/D)-Ratio; the smaller the bend-ratio, the more severe is the bend. Therefore, in order to keep this tradition, the term “bend-ratio (R/D)” will be used as a bending parameter.

Due to the linear strain distributions in cross-section of a bent tube (4, 7-8), the displacement δ would always lead to higher axial and thickness strains on the outside of the bend (tension zone); compared to those on the inside of the bend (Figure 3). This effect can be observed on predicted as well as measured strains around the tube circumference (Chapter 3).

PREDICTION OF STRAINS IN BENT TUBES - When hydroforming bent tubes, the most critical and formability restricted area is the tension zone (outside of the bend). This area experiences the highest axial strains and thickness reduction, and consequently higher material work-hardening due to bendforming. Combining the work-hardening effect and non-uniform thickness distributions in the bend region with a desire to expand the tube cross-section via High Pressure Hydroforming (HPH), can lead to a material failure before the bent tube can take its final shape prescribed by the die cavity. In severe cases where material formability is exhausted during bending, even low pressure hydroforming or pressure sequence hydroforming can fail just because of the reshaping and piercing in hydroforming die. Thus, from a Design and Manufacturing Engineering point of view, the understanding of material behavior and prediction (or realistic estimation) of bend strains is a very important step.

In metalforming processes such as tube bending, the **formability limit** of the tube material on one hand and the degree of the maximum deformation (strains) a part may experience in a given forming process on the other hand are two decisive criteria used to assess the stability of a process and manufacturability of a given part. As long as the maximum deformations in a tubular part are below the formability limit of its material, there is good reason to assume that the tube will survive the process. Therefore, a poor understanding of material behavior while subjected to a bending process and not knowing the maximum level of induced strains will lead to an inadequate prediction of possible material failure or improper material selection.

As mentioned, in rotary draw bending process the highest compression strains occur at the inner and the highest tension strains at the outer point of the bend

region, where the deformations are expected to be the highest. The Relationships 2-4 were developed to determine the maximum principal true strains at the inside of the bend in accordance with geometrical relations in Figure 3 and implementing δ (Equation 1); with “R” as the bend radius, “D” and “t” as tube’s outside diameter and initial wall thickness respectively:

True axial strain:

$$\begin{aligned} \varepsilon_i &= \ln(l/l_0) = \ln((R - 0.5D)/(R - \delta)) \\ &= \ln((1 - 0.5(D/R))/(1 - 0.25(D/R)^2)) \quad /2/ \end{aligned}$$

True thickness strain:

$$\begin{aligned} \varepsilon_t &= \ln(t/t_0) \approx \ln((R - \delta)/(R - 0.5D + 0.5t_0)) \\ &= \ln((1 - 0.25(D/R)^2)/(1 - 0.5(D/R) + 0.5(t_0/R))) \quad /3/ \end{aligned}$$

The true hoop (circumferential) strain ε_h is obtained by applying the principal of constant volume as follows:

$$\varepsilon_i + \varepsilon_t + \varepsilon_h = 0 \quad \Rightarrow \quad \varepsilon_h = -(\varepsilon_i + \varepsilon_t) \quad /4/$$

As Equation 2 indicates, the true axial strain ε_i in the inside of the bend is only a function of the bend severity or the Bend-Ratio “R/D”. This means also that, for a given bend-ratio, the bending strains are always the same (independent of tube material and tube outside diameter). The Equations 3 shows that the true thickness strain ε_t depends slightly on the initial tube wall thickness. However, the thickness term can be neglected for large bend radii and/or smaller wall thicknesses. The principal true strains at the outside of the bend can be obtained in analogy to the Equations above and the geometrical relations in Figure 3.

The strain distributions around the circumference of bent tubes were determined by considering the linear strain transitions in tube cross-section (4, 7, 8) between the highest absolute strains calculated for outside and inside of the bend. Those strain distributions were used here to evaluate the correlations between the predicted strains and measured strains.

Figure 4 visualizes the influence of different bend-ratios on predicted axial and thickness strain distributions around the circumference of bent tubes. The dashed-curves present the axial strains and the continuous-curves present the thickness strains in both the tension zone (left part of the diagram) and the compression zone (right part of the diagram). The curves start from the neutral-axis (at 0° angular position) and develop towards the bend outside continuing around the entire circumference of the bent tube.