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Formability Assessment of Hot Rolled Steel Grades Used for Tubular Hydroforming Application

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Abstract

Tubular hydroforming, the process which uses high pressure to form desired complex shape quickly and easily is the future of automotive industry and is quickly becoming a worthy challenger to the conventional metal stamping and welding. The growing demand for light weight parts in the various fields like automotive, aircraft and aerospace industries have increased the scope for tubular hydroforming in the last few years. The primary advantages of the process are improvement in structural stiffness and crash behavior due to lack of welds and reduced cost assembly.

Hydroforming application demands a clear understanding of material process property relationships. Design, material selection, manufacturing and processing of tubes for this particular application remains critical. Proper understanding of material properties and its forming behavior is the basic necessity for material selection. The effect of material properties on hydroforming process of tubes was investigated. Experimental and FEA studies on free expansion of tubes have been carried out in different materials and materials were ranked based on the suitability for hydroforming. The effect of strain rate on formability of steel sheets was discussed.

Keywords: Formability • Assessment • Tubular • Hydroforming

Introduction

HSLA and AHSS grades are preferred for the application because of its combination of better formability and strength [1]. The effect of pre-bending and hydroforming parameters on the formability of AHSS tubes was discussed. The work states that bending parameters like bending boost, R/D ratio, lubrication and hydroforming parameters like end feed, corner fill expansion play a key role on formability of AHSS. Forming Limit Diagrams (FLD's) are an important tool for sheet formability investigations. It is used to measure maximum formability of material. Some of the test methods available to determine the formability of sheet metal, tubes through FLD are Sheet Nakazima tests, tube Nakazima tests, tube burst test and hydraulic bulge test/free bulge tests. Hydraulic bulge test was done to determine the stress strain characteristics of different tubular materials. Experimentation as well as numerical simulation of bulge testing has been carried out in these works. Few empirical relations have also been proposed by researchers to predict the plane strain forming limit FLD [2].

Many researches focusing on the numerical simulation of tubular hydroforming have been carried out in the past to reduce cost and time. Tooling, prediction of necking, optimization of process design, hydroforming parameters etc are few such works. Wall thickness distribution of the hydroformed tubes was determined through FEM simulation and experimentation. Also, he investigated the effect of process parameters and material properties on uniform wall thickness distribution of hydroformed tubes [3].

A collective study on different material properties influencing the sheet metal formability has not been carried out. The aim of present work is to evaluate the formability of different hot rolled steel grades used for tubular hydroforming application by determining Forming Limit Diagrams (FLD's) through experimentation. Studies were carried out in sheet metal used for manufacturing of tubes for THF application. Also the effect of mechanical properties on the formability of material has been investigated [3].

Materials and Methods

Three steel grades of chemical composition as listed in the hot rolled condition were used for the study. The carbon content and alloying element content vary significantly among the three grades (Table 1) [4].

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	Thickness (mm)	C	Si	Mn	Al	Nb	V	Ti
E34	2.6	0.072	0.005	0.51	0.039	0.016	0.002	0.014
E46	3.2	0.058	0.088	0.889	0.028	0.05	0.03	0.001
SAE 1020	2.6	0.146	0.076	0.833	0.03	0.024	0.001	0.018

Table 1. Chemical composition of the steel grades (wt %).

Microstructure of the steel grades was examined using ZEISS Light optical microscopy and JEOL Scanning electron microscope. Grain size estimation and phase fraction studies were carried out. Tensile samples were extracted from the sheet metal at different orientation like 0°, 45° and 90° to rolling direction. Testing was carried out as per ASTM E8 using 330 kN Zwick Roell UTM to determine the mechanical properties. For each material, plastic strain ratio in each direction was determined and then average normal anisotropy was calculated as per ASTM E517 [5].

Hole Expansion Test (HET)

Hole Expansion Tests (HET) were done generally to assess the edge formability characteristics of a material (Figure 1). The experimental apparatus used for the test hole of diameter 10 mm is pierced at the centre of 100 mm diameter circular sample using a circular punch and later the hole is expanded using a conical punch, whose included angle is 60°. The test is conducted as per ISO 16630 standard. The test is performed till crack initiates at the edge of the hole. Hole Expansion Ratio (HER) is calculated using Equation 1.

$$HER=100\,[(D_f-D_0)/D_0] \quad \text{(Equation 1)}$$

Where, HER-Hole Expansion Ratio D_f-Final diameter of the hole after test D_0-Initial diameter of the hole before test

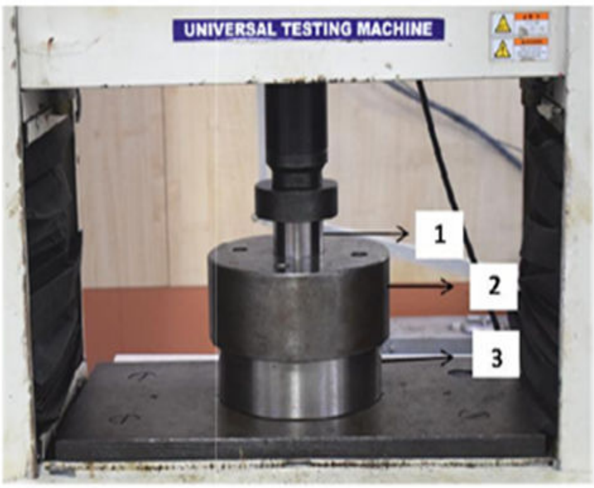

Figure 1. Hole expansion test set up in UTM. Note: 1-Punch, 2-Punch holder, 3-Die holder.

Forming limit diagram determination through limiting dome height test

Forming limit diagrams are determined by conducting Limiting Dome Height (LDH) tests using universal testing machine of 1000 kN capacity. A unique tool setup to conduct LDH tests for sheet metals of thickness greater than 2 mm was developed. The experimental procedure involves three stages-grid marking the samples, forming using punch until cracking or onset of necking and strain measurement (Figure 2) [6].

1. Grid marking was done on the sheet metal samples through laser marking technique [7].
2. The grid marked samples which are of varying width, were formed using a hemispherical punch of 100 mm diameter until fracture or onset of necking of dome [8].
3. After deformation, the circular grids become elliptical and the major and minor strains of the deformed ellipses in safe, necking and fractured zones were measured. Strain distribution in the formed samples was measured using grid pattern analyzer 3.0 software [9].
4. The Grid Pattern Analyzer (GPA) is a single point strain measurement system. The system is comprised of a video camera system for data acquisition, software for data processing and analysis, and a computer. The camera was placed in various zones of the deformed sample and strain measurement was done [10].
5. Lastly, the Forming Limit Diagram (FLD) of the sheet metal was plotted by the software using the major and minor strains [11].

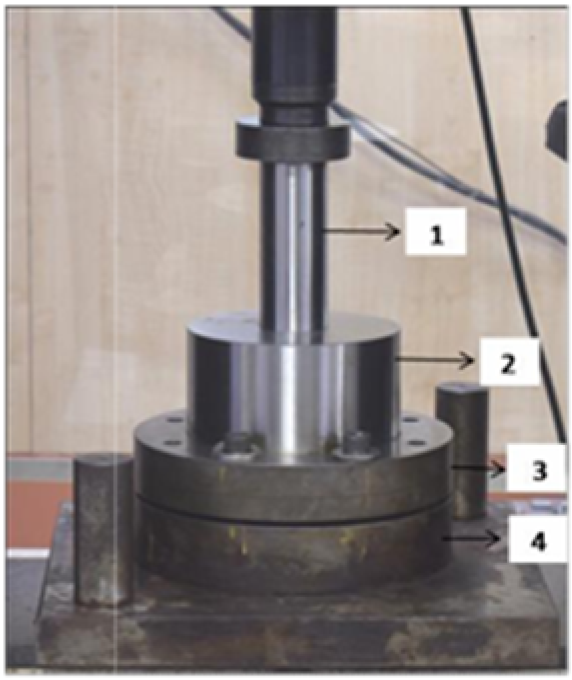

Figure 2. Limiting dome height test set up in UTM. Note: 1-Punch, 2-Punch holder, 3-Top die, 4-Bottom die.

Results

Microstructural characterization

To understand the influence of microstructure on formability, microstructural characterization of the three grades was carried out. The microstructures of the steel grades taken along the rolling direction respectively. Ferrite pearlite microstructure was observed in all the three cases but their phase fraction and grain size varies significantly. ASTM grain size of E34, E46 and SAE 1020 measured using CLEMEX image analysis software are 20 µm-25 µm, 5 µm-10 µm and 5 µm-10 µm respectively. The same results were confirmed using SEM (Figure 3) [12].

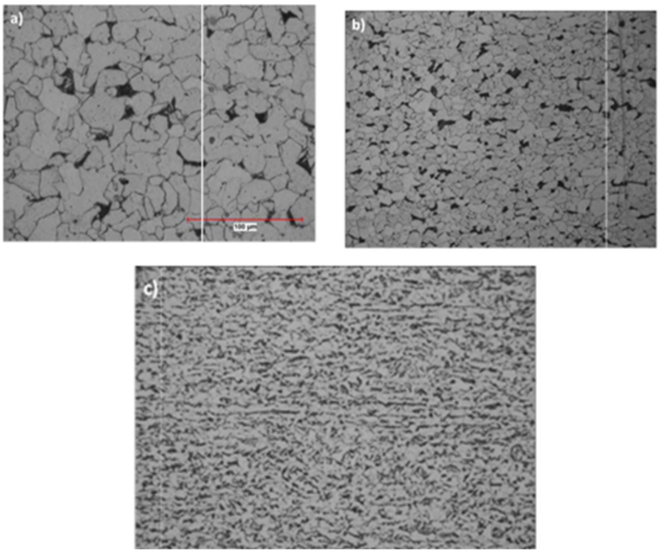

Figure 3. Microstructure of a) E34 material; b) E46 material; c) SAE 1020 material taken along the rolling direction.

Mechanical properties

The true stress-true strain curves of the three hot rolled steel grades along the RD obtained from uniaxial tensile tests. Yield point phenomenon is evident in all the three cases from the flow curves. Lists the mechanical properties like strain hardening coefficient (n), ratio of Yield Strength to ultimate Tensile Strength (YS/TS), ratio of Uniform Elongation to Total Elongation (UE/TE) and elongation at fracture and compares the YS, UTS of the three materials. It is observed that E46 has higher strength when compared to other two materials and E34 has higher total elongation than other two materials (Table 2) (Figures 4 and 5) [13].

	Strain hardening exponent (n)	YS/UTS	UE/TE	Elongation at fracture (%)
E34	0.19	0.895	0.739	23
E46	0.13	0.935	0.578	21.5
SAE 1020	0.16	0.768	0.708	22

Table 2. Mechanical properties of the three steel grades.

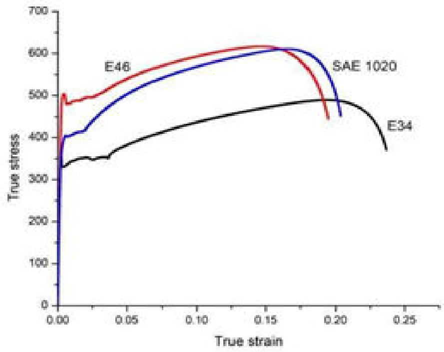

Figure 4. True stress-true strain plot of the three steel grades.
Note: — E46, — E34, — SAE 1020.

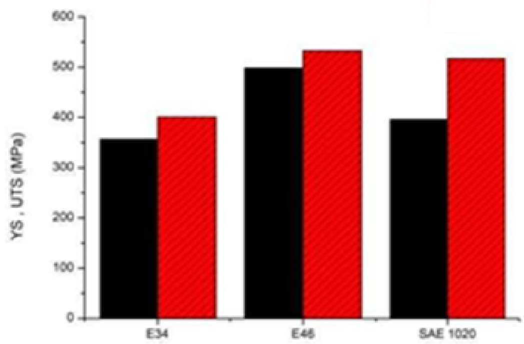

Figure 5. Comparison between YS and UTS of the steel grades.
Note: ■ YS, ■ UTS.

Fracture surface of the tensile samples were observed using scanning electron microscope. The SEM micrographs of the fractured surface clearly show presence of micro void coalescence features indicating that all the three steel grades have failed in a ductile manner. Plastic strain ratio determined in different orientations (0°, 45° and 90°) and normal anisotropy values are tabulated. Normal anisotropy value of E46 is slightly higher than other two grades. Also, the significant in E46 material. Variation in plastic strain ratio between 0°, 45° and 90° is significant in E46 material (Figure 6) (Table 3).

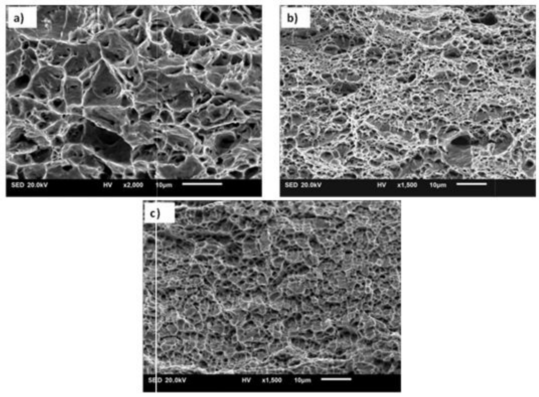

Figure 6. Scanning electron image showing fracture surface of tensile samples of a) E34 material b) SAE 1020 material and c) E46 material.

	R0	R45	R90	Normal anisotropy (r)
E34	0.688	0.99	0.701	0.843
E46	0.62	1.32	0.847	0.943
SAE 1020	0.663	0.99	0.7095	0.838

Table 3. Anisotropy values of the three steel grades.

Hole Expansion Tests (HET) results

Table 4 summarizes the average HER of the three steel grades tested using the hole expansion test set up. Minimum four samples from each grade were tested. The test is stopped at the point of through thickness crack generation from the hole edge. The diameter of the expanded hole i.e from hole center to hole edge serves as the measure of HER. The image of a tested sample showing the presence of crack (Table 4).

Material	Hole expansion ratio
E34	82.8
E46	89.2
SAE 1020	81.6

Table 4. Her of the three steel grades.

The reported values are average of four tested samples (ISO/TS 16630) (Figure 7).

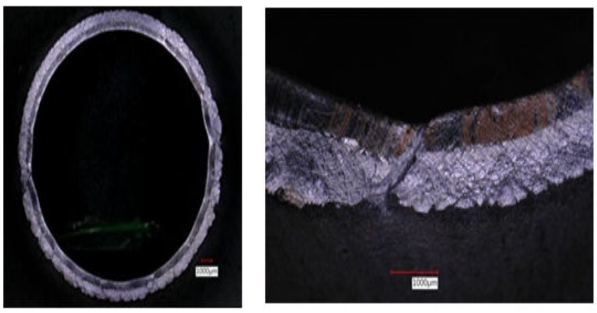

Figure 7. Surface of hole expanded sample.

Forming limit diagram determination

Experimentation-limiting dome height test: Limiting dome height test of each material includes testing of set of eight samples of varying width. Samples from 25 mm to 75 mm width lie in uniaxial load path while sample with 100 mm lies in strain plane condition. Samples from 125 mm to 200 mm width exhibits biaxial stretching path in the FLD plotted. Sheet metal samples were formed using the tool setup until onset of necking or cracking.

The load *vs.* displacement curves are obtained from the test. Major strain and minor strain values measured using GPA software near the necking zone of formed samples was used to plot the forming limit curves of the different materials. The comparative FLC's of the three steel grades. FLC of E34 material lies above the other two steel grades.

In order to generate FLD, n value of each material and its corresponding thickness was fed to the software. The software calculates the plane strain forming limit (at zero minor strain) of the different materials based on Equation 2.

$$FLD0=(67.304t+110.95)n \quad \text{(Equation 2)}$$

Where, FLD0-Plane strain forming limit t-thickness of material (mm) n-Strain hardening exponent.

The FLD0 values of E34, SAE 1020 and E46 determined are 0.43, 0.37 and 0.35 respectively (Figures 8 and 9).

Figure 8. Image showing the LDH samples before testing.

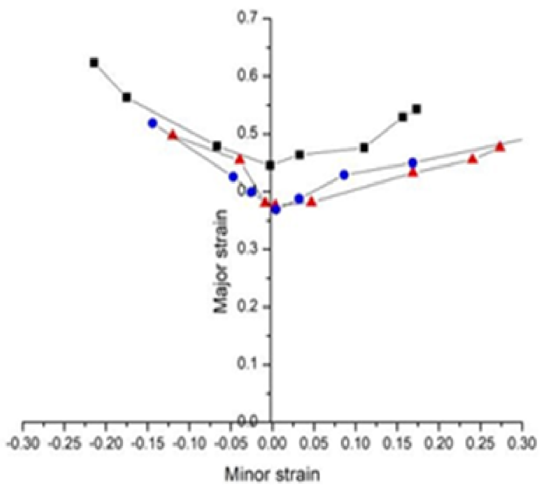

Figure 9. Forming limit curves of the three steel grades.
Note: ■ E34, ▲ SAE 1020, • E46.

Discussion

Hot rolled steels with microalloying additions of Nb, Ti and V were chosen for the study. The principal effects of Nb and V addition are refinement of microstructure and strengthening. Niobium is the most effective microalloying element in retarding recrystallization of hot worked austenite whereas Ti primarily controls grain growth [7]. Higher alloying content in E46 and SAE 1020 material contributes to its higher strength and finer grain size. Low UTS of E34 could be attributed to its coarse grain size as per Hall-Petch relationship [8]. Studied the effect of thickness on formability. It shows that increase in thickness shifts the forming limit curve upwards. Actually the FLC of E46 should lie above the other two grades owing to its higher thickness of 3.2 mm. But experimental results show that FLC of E46 lies below that of E34 material. The lower n value of E46 might be a reason for this behavior. Thus n value plays a dominating role over thickness in deciding the formability of sheet metal. Local thinning which causes fracture proceeds in case of materials with low n value and r value.

Despite its higher UTS, E46 exhibits early failure during LDH tests and its limiting strain values are low.

This might be due to low UE/TE ratio. E34 exhibits high UE/TE ratio indicating delayed necking behavior, which is beneficial for hydroforming application. Thus, ratio of uniform elongation to total elongation plays a vital role in determining formability. Also it is to be noted that E34 exhibits low YS ~355 MPa and higher percentage of total elongation ~24. Generally materials with low YS and high ductility generally perform well in hydroforming.

Hydraulic bulge test is a direct test method for assessing the material's suitability for hydroforming application. However in this work, FLDs' are used for comparing the steel grades since the technique is simpler and cost effective. While forming limit diagrams are used to determine bulk sheet formability, hole expansion test provides better understanding of local/edge formability characteristics of each material. In his work, the study is clearly discusses different models to predict HER analytically from uniaxial tensile properties. The empirical formulas suggest that when average anisotropy increases, HER increases. In the present work, E46 grade with r bar value 0.943 has the highest HER of 89.2 among the three steel grades. Since the three materials doesn't show significant in r bar value, effect of it on FLC could not be validated in detail through this study. However literatures suggest the use of materials with high r value for tubular hydroforming applications. It is also inferred from present study that HER does not affect FLC to a greater extent.

Apart from better uniaxial tensile properties, it is also experimentally proved through FLD that E34 performs well in biaxial stretching zone. Hence the study suggests that E34 is preferable for tubular hydroforming application than other grades. Thus, among the different material properties, n value, UE/TE ratio and yield strength are the primary factors deciding the forming behavior of material. In most cases, coarser the grains are better is its formability.

Conclusion

The study focuses on determining FLDs of few high strength low alloy steel grades used for tubular hydroforming application thereby aiding in material selection for the application based on formability. Through this work, the effect of uniaxial tensile properties like n value, r value, total elongation, Uniform elongation to total elongation ratio, strength on FLC was studied. Also, the influence of grain size on formability is assessed. The relation between hole expansion ratio and FLC was understood. Limiting Dome Height test for constructing FLD of high thickness (>2 mm) sheet metals has been tried out successfully E34 steel grade is suggested as a preferred choice of material for manufacturing tubes for THF application among the three steel grades. Materials with high n value, high uniform elongation to total elongation ratio, low YS, high total elongation, coarse grain size are suggested for tubular hydroforming through this study.

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