Anisotropy Induced Biaxial Stress-Strain Relationships in Aluminum Alloys

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Abstract: 5XXX series of aluminum alloys are a category of novel alloys suitable for construction of ship hulls and the topside structures of offshore platforms. Within different 5XXX aluminum alloys, AA5083 is of great importance which is extensively used in ship construction industry. In the present study, formability of AA5083-H111 aluminum alloy is investigated at room temperature using uni-axial tensile tests and hydraulic bulge tests. Tensile tests were performed to evaluate material anisotropy in different directions with respect to rolling direction. Anisotropy coefficients were then used to correct flow stress curves obtained by balanced biaxial bulge tests. Moreover, flow stress curves obtained from both tests were separately introduced to an explicit commercial finite element code. Comparisons showed that numerical simulation carried out in this study stand in according with empirical results.

Keywords: AA5083, Anisotropy, Autoform, Bulge test, Tensile Test

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1 INTRODUCTION

5XXX series of aluminum alloys are commonly used in the manufacture of unheated, welded pressure vessels, marine equipments, auto aircraft cryogenics, drilling rigs, TV towers, transportation equipment, and in missile components. Ships are the largest moving structures constructed worldwide. Due to corrosive environment of sea water, when manufacturing this gigantic structure, corrosion resistant materials must be applied. Its high strength and corrosion resistance combined with being a light weight alloy has increased the demand for 5XXX and 6XXX series of aluminum alloys especially in ship construction.

AA5083 (AlMg4.5Mn) aluminum sheet alloy is the most frequently-used alloy which is extensively used in ship building in the form of sheets and plates. High-strength properties as well as corrosion resistance of this alloy are due to its magnesium content of about 5% in its chemical composition.

To form this aluminum alloy into a proper shape when constructing a ship, forming behaviors under different states of stress must be considered. Common mechanical tests to evaluate flow behavior of sheet materials under biaxial and uni-axial stress state are the hydraulic bulge test and conventional tensile test, respectively. Biaxial flow stress results deduced from the balanced biaxial bulge test are used for finite element simulation of sheet metal deformation processes in conjunction with the fact that in sheet metal forming operations the state of stress is usually planar. Since mechanical properties of rolled sheets are influenced by rolling conditions, for the tensile test, tension specimens in three different directions with respect to rolling direction (0º,45º and 90º) should be cut and tested to evaluate the mechanical property variations between different rolling directions.

The first theoretical pillar for the hydraulic bulge test was established by Hill [1]. By assuming the deformation region, to be circular at the top of the dome, he expressed a closed form solution for the thickness at the dome apex. By taking into account that strain hardening exponent plays a significant role in thickness distribution, Chakrabarty et al [2] improved Hill's pole thickness model. More recently, Gutscher et al [3] implemented a novel approach to investigate mechanical properties of aluminum and steel sheets through the bulge test. He used a viscous material instead of hydraulic oil to apply hydrostatic pressure on the sheet material to be formed. Afterwards, Nasser et al. determined the flow stress curves for five advanced high strength steels through the novel method proposed by Gutscher [4]. In his study, Nasser corrected flow stress curves for anisotropy obtained from bulge test by using Hill'90 yield criterion. Fig. 1 shows a schematic view of the hydraulic bulge test in which a sheet metal is deformed under biaxial state of stress. During this mechanical test, sheet metal is fully clamped at flange area to ensure pure stretching.

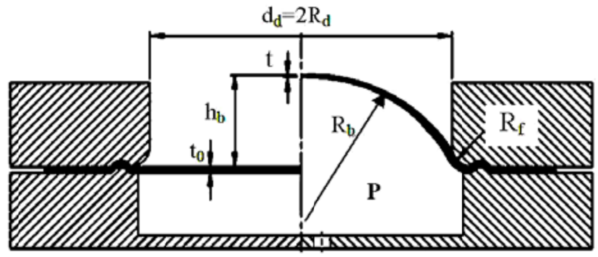

Fig. 1 Schematic view of hydraulic bulge test

The main objectives of this study are to establish a framework to:

1) Determine flow stress curves in both biaxial and uni-axial state of stress for 1mm AA5083-H111 sheets.
2) Compare flow stress curves obtained from hydraulic bulging with those resulted from uni-axial tension.
3) Finite element simulation of bulging process and investigating biaxial stress-strain relationships in sheet metal forming simulation processes.

2 THEORETICAL BACKGROUND

The membrane theory of plasticity is one of the most common analytical approaches for hydraulic bulging to investigate the flow stress curves [5], [6]. For a spherical membrane with very small thickness-to-radius ratio, the in-plane stresses resulted from bulging is much larger than the bending stresses. Consequently, the bending stresses can be neglected from this analytical approach with negligible error. Thus, this assumption is only applicable for thin sheets in order to identify a relationship between stresses, sheet curvature radii and bulge pressure.

If the bulge profile is considered axi-symmetric, $\sigma = \sigma_\theta = \sigma_\varphi$ and also the radius at the bulge dome is $r = r_\theta = r_\varphi$. Therefore the major true stress can be written as follows:

$$\sigma = \frac{pr}{2t} \qquad (1)$$

Assuming Von-Mises's plastic flow criterion conjunction with Hill'48 [7] yield criterion the effective stress can be written as follows:

$$\bar{\sigma} = \sigma[2 - \frac{2R_{ave}}{(R_{ave}+1)}]^{0.5} \quad (2)$$

Principle strains at dome of the bulge are ε_θ , ε_φ and ε_t Assuming Von-Mises yield criterion and letting $\varepsilon_\theta = \varepsilon_\varphi$, the effective strain can be calculated as:

$$\bar{\varepsilon} = \sqrt{\frac{2}{9}\left[(\varepsilon_\theta - \varepsilon_\phi)^2 + (\varepsilon_\theta - \varepsilon_t)^2 + (\varepsilon_\phi - \varepsilon_t)^2\right]} \quad (3)$$

Considering the principle of volume constancy ($\varepsilon_\theta + \varepsilon_\varphi + \varepsilon_t = 0$), the effective strain is:

$$\bar{\varepsilon} = -\varepsilon_t = \ln\frac{t_0}{t} \quad (4)$$

In order to draw an effective stress versus effective strain curve, two variables (t and R_b) are needed to be measured in every time step during the bulging process. Table 1 contains theoretical approaches to calculate sheet thickness at the dome apex.

3 DESIGN OF THE EXPERIMENT

3.1 Hydraulic bulge test

The experimental approach was carried out on a 1mm AA5083-H111 aluminum sheet alloy in so far as this alloy is significantly applicable in the ship construction industry. The experimental apparatus used to implement the hydraulic bulge test is composed of a tooling set, a hydraulic power generator and measurement devices. For the toolset accomplished, maximum forming pressure can reach 50MPa (500bar). This pressure is greatly sufficient for hydraulic bulging of 1mm AA5083-H111 sheet alloy. In order to seal the die the rubber diaphragm was precisely placed between the conical part of the die and the conjunctive disc. In this way, hydraulic bulging of different materials can easily be carried out. A pressure gauge and an indicator were used to measure the chamber pressure and bulge height respectively during the bulging process. The indicator used in the experiment is delicate and could not withstand impact loads as the specimen bursts. Hence, for bulge testing of AA5083-H111 at least three samples were burst with the absence of the indicator to discern the bursting pressure. Other samples were tested up to 90% bursting pressure while the indicator was used to measure the bulge height during the process. In order to ensure pure stretching, draw beads were used around the bulging region. First of all, using a 300ton hydraulic press, aluminum sheets were stamped into the draw bead and then the specimens were prepared for being bulged. Fig. 2 shows a hydroforming die used for bulge testing of sheet materials.

Table 1 Theoretical approach to calculate thickness at top of the dome

Dome radius thickness calculation at the dome apex		
Hill [1]	$R_b = \frac{d_d + 4h_b}{8h_b}$	(5)
Gutscher [3]	$R_b = \frac{(R_d + R_f)^2 + h_b - 2R_f.h_b}{2h_b}$	(6)
Sheet thickness calculation at dome apex		
Hill [1]	$t = t_0(\frac{1}{1+\left(\frac{h_b}{R_d}\right)^2})^2$	(7)
Chakrabarty et al [2]	$t = t_0(\frac{1}{1+\left(\frac{h_b}{R_d}\right)^2})^{2-n}$	(8)
Kruglov [8]	$t = t_0\left[\frac{\left(r_d/R_b\right)}{Sin^{-1}\left(r_d/R_b\right)}\right]^2$	(9)

Measuring devices were also calibrated before testing to ensure precise measurement. In order to prevent draw-in of the sheet material to the die cavity, a draw bead was used. Consequently, pure stretching of the sheet material was seen during the bulging process. After being bulged to a certain height, the chamber pressure was measured using a pressure gauge. The expanding height at the pole of the bulged sheet was detected by an indicator. Afterwards, the forming pressure increased to reach the next bulge height level.

Fig. 2 Hydroforming bulge test apparatus

3.2 Tensile test

To omit edge effects associated with shearing processes, uni-axial tensile specimens were cut by wire EDM according to ASTM-E8 standard (Fig. 3). to eliminate errors resulted from misalignment of tensile specimens when tensile testing is being carried out, at least two samples at each direction (0º, 45º and 90º) with respect to rolling directions were precisely cut. Tensile tests were carried out according to ASTM-E517-00 standard. This standard deals with anisotropy of sheet materials as well as yield and tensile strength and the elongations in different directions with respect to rolling direction. During the tests, in addition to an extensometer, which monitors longitudinal elongations and the corresponding longitudinal strain, a strain gauge was used to monitor the width strain simultaneously. Consequently anisotropy of the sheet material could be obtained. Tensile tests were carried out under the constant strain rate of 1×10^{-3} S^{-1} at room temperature. After conducting the tensile test, the recorded tensile forces versus specimen's elongation were converted into true stress against true strain as well as engineering stress-strain curve.

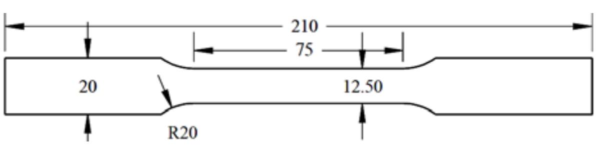

Fig. 3 Tensile test dimensions cut according to ASTM-E8 standard

Although R-value is introduced as the ratio of width strain to thickness strain, the thickness strain, ε_t, in thin sheets could not be accurately measured. Hence, by measuring longitudinal and width strains and also by implementing the principle of volume constancy, the thickness strain can be obtained as follows:

$$\varepsilon_l + \varepsilon_w + \varepsilon_t = 0 \quad (10)$$

$$\varepsilon_t = -(\varepsilon_l + \varepsilon_w) \quad (11)$$

For each direction, the strain ratio (R-value) was calculated. Subsequent to that, normal anisotropy as well as planar anisotropy was calculated according to International Standard ASTM E517-00 formulas [9]. Equations 12 and 13 show how normal and planar anisotropy are obtained.

$$R_{(x)^\circ} = \frac{\varepsilon_{w(x)^\circ}}{\varepsilon_{t(x)^\circ}} \quad (12)$$

$$R = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

$$\Delta R = \frac{R_0 + R_{90} - 2R_{45}}{2} \quad (13)$$

In the above equations, R is the normal and ΔR is the planar anisotropy.

4 FINITE ELEMENT APPROACH

Forming characterizations rely heavily on the experience of the process design engineer. Iterative trial-and-error development cycles are time-consuming and costly. In order to validate the numerical approach used in this paper, biaxial flow stress curve obtained from the experiment was used as an input data to numerically simulate bulge test through Autoform Master 4.4 commercial code. Autoform software is extensively used in sheet metal forming industries. For the FE modeling, first CAD data were modeled in CATIA software and then were imported into Autoform environment (Fig. 4). Material properties obtained from both uni-axial and biaxial tests were introduced to the software. An active pressure was exerted under the sheet material and the process time considered as 10sec. In the modeling both holder and pressure chamber were considered as rigid parts. Friction coefficients were adjusted to 0.15 for contact surfaces. Resulted bulge pressure versus dome height curve was then compared with the experimental one.

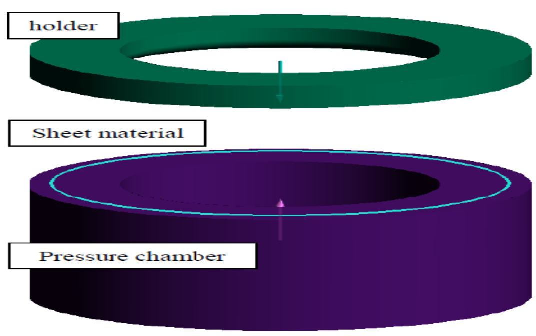

Fig. 4 Finite element modelling of bulge test in Autoform 4.4 software

5 RESULTS AND DISCUSSION

In Table 2 mechanical properties of AA5083-H111 are tabulated in three directions relative to the rolling direction. As it can be observed from the Table, maximum elongation is obtained at 45 degrees with respect to the rolling direction. Average normal anisotropy obtained from the test shows that this material is sensitive to thinning and can not withstand large deformation during sheet metal forming operations. On the other hand, the planar anisotropy shows that this material is not sensitive to earring during the deep drawing process. Higher values for the planar anisotropy will result in earring, in stamping and deep drawing processes. In order to define the flow stress curve for AA5083-H111 in biaxial state of stress, seven bulging samples were used. At least three samples were burst to realize the bursting pressure. The burst pressure obtained from bursting sample #1 was 104 bars and bursting pressures for samples 2, 3 and 4 were 108, 106 bars, respectively. Hence, bursting pressure for 1mm AA5083-H111 aluminum sheet in this study was considered to be 106bars. Fig. 5 shows experimentally measured bulging pressure versus dome height up to 95 bars pressure.

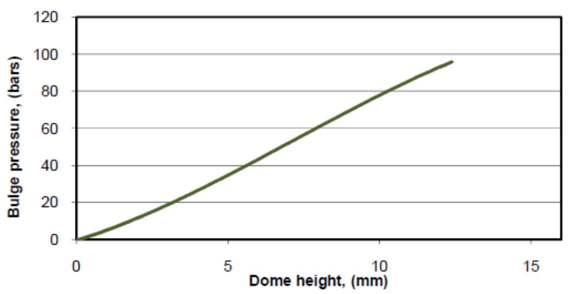

Fig. 5 Experimental pressure versus dome height curve for AA5083-H111

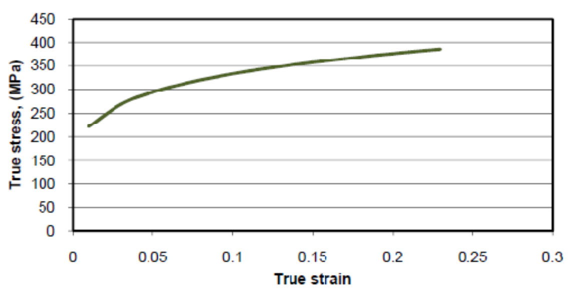

Fig. 6 True stress-true strain curves for AA5083-H111 obtained from hydroforming bulge test.

The corresponding flow stress curve is illustrated in Fig.6. As discussed before, due to the fact that bulge height measuring devices are delicate, when using an indicator, bulging of sheet metal was carried out up to 95 bars pressure (about 89% of bursting pressure). To define the flow stress curve up to bursting point, the experimentally measured pressure versus dome height was extrapolated using third order polynomial approximation. The extrapolated curve is shown in Fig. 7. Fig. 8 shows extrapolated flow stress curve from pressure versus dome height curve. With this extrapolated curve, the full range of flow stress curve for AA5083-H111 in biaxial stress state was obtained. In Fig. 8 it is also shown that a plastic strain of 0.37 is reachable when the sample bursts. Its corresponding true stress is about 425MPa which reveals relatively high strength for AA5083-H111 aluminum sheet alloys. Fig. 9 shows a burst sample (a) and a sample being bulged up to 89% of bursting pressure (b) for 1mm AA5083-H111 aluminum sheet. In the Figure, the left sample is pressurized up to 95bars pressure using the indicator. The right sample shows 1mm AA5083-H111 when reaching the burst pressure.

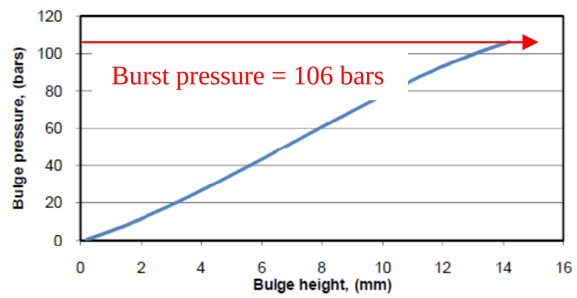

Fig. 7 Experimental pressure versus dome height curve for AA5083-H111 (the curves is extrapolated, using higher order polynomial approximation).

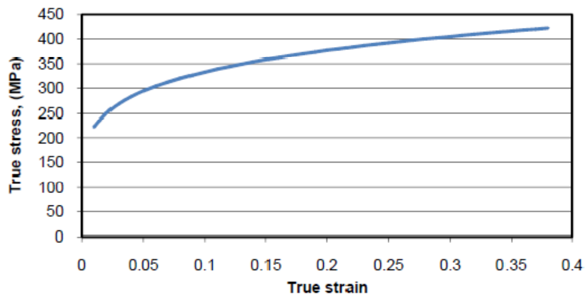

Fig. 8 Corresponding flow stress curve related to experimentally measured bulging pressure vs. dome height (with extrapolation)

Table 2 Mechanical properties of 1mm AA5083-H111 sheets obtained from uni-axial tensile test

Parameters	Angle to rolling direction		
	0º	45º	90º
Density, (gr/cm^3)	2.8	2.8	2.8
Poisson's ratio		0.33	
Elastic modulus, (GPa)	69.5	68.7	71
Yielding stress, (MPa)	178	195	184
Ultimate tensile stress, (MPa)	310	337	318
Total elongation, (%)	23	26	24.5
Anisotropy coeff., R	0.66	1.05	0.667
Normal anisotropy		0.848	
Planar anisotropy		-0.404	
Strain hardening exponent	0.22	0.23	0.21
Hardening coeff. (MPa)	514	521	517

In Fig. 10, flow stress curves were compared between uniaxial test and biaxial bulge test. Biaxial curves are depicted with/without considering anisotropy of sheet material. As it can be deduced from the Fig., in biaxial flow stress curves more strain ranges can be covered compared to uni-axial flow stress. This difference in plastic strain would be 280% for AA5083-H111.

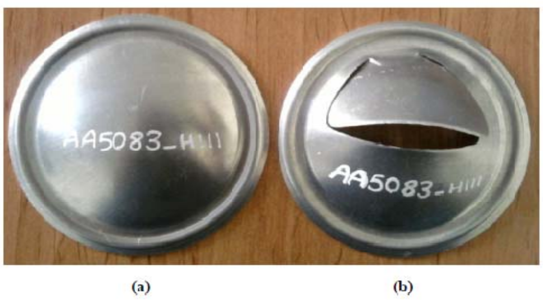

Fig. 9 Hydraulic bulge test samples (a) sample not burst and (b) sample burst

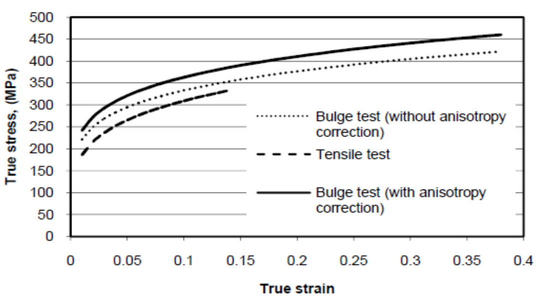

Fig. 10 Comparison between flow stress curves obtained from tensile test and hydraulic bulge test for AA5083-H111 (biaxial curves are extrapolated and uni-axial curve is depicted up to uniform elongation)

5.1 Finite element simulation

Fig. 11 shows the numerical model simulated in the FE software. In Fig. 12, very good consistency for minimum thickness at the dome apex vs. bulge pressure between numerical approach and the experiments are shown. Moreover, in finite element simulation of hydroforming bulge test, bursting pressure of 118bars was obtained although the 1mm AA5083-H111 sheet was burst at 106bars pressure during several experimentations.

Table 3 Comparison of K and n-value obtained by tensile test and bulge test

Test type	K-value (MPa)	n-value
Tensile test	514	0.221
Bulge test	500.4	0.177
FE simulation (with bulge test input)	486	0.165
FE simulation (with tensile test input)	508	0.205

Furthermore, maximum dome height, which expresses the material formability during the bulge test, was 17.58mm in the simulation while from extrapolated experimental pressure vs. dome height, maximum height of 14mm was detected.

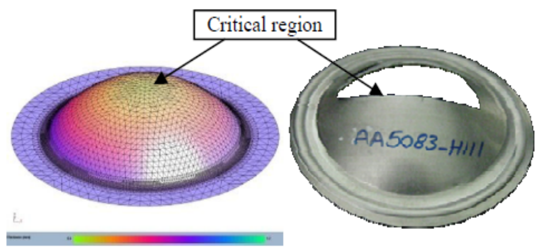

Fig. 11 Finite element simulation compared to empirical results of AA5083-H111experiment

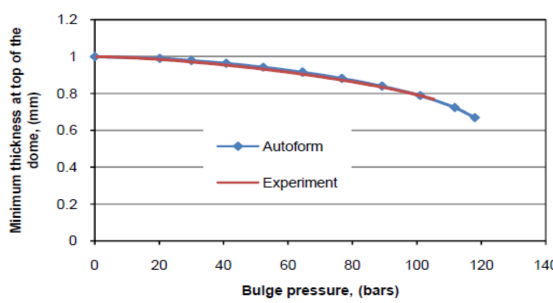

Fig. 12 Minimum thickness at dome apex vs. bulge pressure; comparison between FE simulation and empirical results

6 CONCLUSION

In the present study, forming behaviors of 1mm AA5083-H111 aluminum sheet alloy under uni-axial and biaxial state of stress were evaluated through tensile test, as the preliminary step. Analytical equations were used to determine the biaxial flow stress curves by implementing measured bulging pressure and dome height. Moreover, experimental flow stress curves obtained from bi-axial and uni-axial tests were separately introduced to a finite element code in order to investigate the flow stress curves obtained from simulations.

Based upon experimental and numerical results the following conclusions were drawn:

1. Cold stretchability of 5XXX series of aluminum sheet alloy is much lower than warm stretchability of this alloy at increased temperatures as done by the others [10].
2. Flow stress curves obtained from the hydraulic bulge test cover a wider strain range in comparison with the flow behavior deduced from tensile test.
3. Finite element results were in good agreement with the empirical results obtained from simulation of hydroforming bulge test.

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