Experimental and Numerical Investigations of Deep Drawability of AA1200

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***Abstract*— *The ability of a sheet metal to be formed in a given process without failure is known as formability. Formability is a measure of the amount of deformation a material can withstand prior to fracture or excessive thinning. Forming Limit Diagram (FLD) is a graphical representation of limit strains at which necking/fracture occurs in a sheet metal under all possible modes of deformation. Anisotropy is the variation in properties with respect to directions, due to variations in microstructures introduced in forming operations such as rolling. The values of strength (YS and UTS) and ductility (% elongation) show a large variation in mechanical properties because of the differences in as rolled specimens, annealed specimens, and different thickness of the Al sheets. From the LDH test the limiting strain values and the formability of sheet metal were found to increases with increasing sheet thickness.*

Keywords*— *AA1200 aluminum alloy sheets, sheet forming, stretch forming, anisotropy.

I. INTRODUCTION

Sheet metal forming is a process in which flat thin blanks are deformed permanently to produce a wide range of products i.e. very simple sheet metal parts to complex three dimensional objects. These operations are widely used in industry and hence knowledge of various sheet metal forming processes is essential to manufacture good quality products. Common parts made by sheet metal forming processes include automobile body panels, fuel tanks, aircraft parts, various parts for building industries and also for making domestic home appliances, food and drink cans. Steel and its various grades are used for a variety of sheet metal parts. Plain low carbon steels have a large application in automotive industries. The advances in material processing has led to development of wider range of advanced steel grades like extra deep drawing steels and interstitial free steels for critical forming applications.

Aluminium alloys are now-a-days replacing the steel in automobile industry since they have lower weight, comparable strength and high corrosion resistance and they reduce the vehicle weight and hence able to achieve better fuel consumption [Zhongqi Yu, 2007]. Aluminium alloy selection depending on the above mentioned properties may look better, but the manufacturing aspect also needs to be considered. For example the bumpers should combine strength and also adequate formability. Hence the formability of aluminium alloys needs to be studied. Because of their inferior forming properties, advanced methods are being used to exploit their full potential. Large number of aluminium alloy sheets has been developed in the recent past for potential application in automotive industry.

The experimental determination of forming behavior of these modern materials is time consuming which necessitates some easier methods of determining formability. Finite element simulation or theoretical methods are finding wider importance now-a-days. This can lead to the optimization of process and design variables to achieve better quality stampings.

II. LITERATURE REVIEW

Experimental evaluation of formability

Formability tests

Some lab tests used to determine formability are briefly explained below:

The Swift-cup test [George E Dieter, 1988] is a drawing test. A series of blanks with steadily increasing diameters are deep drawn, and at one point a diameter is reached, where the punch penetrates the not yet completely drawn cup. The Swift cup test is the determination of the limiting drawing ratio (LDR) for flat-bottom cups. A simulative test in which circular blanks of various diameters are clamped in a die ring and deep drawn into a cup by a flat-bottomed cylindrical punch.

The Swift Cup test is usually considered to provide a measure of the drawability of sheet metal. A disc-shaped sheet specimen of metal is placed between the blank holder and the die and then it is drawn into a cup by a cylindrical punch. A cup with a cylindrical shape will be form after the test. The sheet is drawn which is held under a blank holder, properly lubricated to ensure material flow. The limiting draw ratio (LDR) which is the ratio of the maximum blank diameter that can be drawn without fracture to the cup diameter is the measure of drawability. A high Swift number indicates a good drawability and vice-versa.

The Erichsen & Olsen tests [George E Dieter, 1988] are used to estimate sheet metal formability under pure stretching conditions. The sheet is clamped between two flat plates and is stretched by a ball. Cups are formed by stretching over a hemispherical tool. The height of the cup represents the formability index. Cups with larger height represent good resistance to necking. The results depend on stretchability rather than drawability. The Erichsen and Olsen test produce bending strains in the test and hence no longer used in the industry.

The cupping tests discussed above are losing favour because of irreproducibility. Hecker attributed this to "insufficient size of the penetrator, inability to prevent inadvertent drawing in of the flange, and inconsistent lubrication." He proposed the limiting dome height test (LDH) [Hosford and Caddel]. The specimen width is adjusted to achieve plane strain and the flange is clamped to prevent draw-in. The limiting dome height (LDH) is the greatest depth of cup formed with the flanges clamped. The LDH test results correlate better with the total elongation than with the uniform elongation. This test is widely used in the industries.

III. EXPERIMENTAL SET UP AND PROCESS PARAMETER

Selection of materials.

Sheet metal for present work is Aluminium Alloy 1200 grade is as rolled, of thickness of 1mm and 1.6mm.As rolled metal sheets are those sheets which are come directly from the roll mill. The properties of as rolled sheets are changes to anisotropic from isotropic soon after the annealing of the sheet metal.

Table.1: Chemical composition of the as rolled AA1200 used (by weight %).

Si	Fe	Cu	Mn	Al
0.0929	0.451	0.0026	0.0022	99.37
Mg	Cr	Ni	Zn	
0.0017	<0.00050	0.0022	0.0073	
Ti	Pb	Sn	V	
0.0271	0.0148	0.0067	0.0013	

Annealing

The sheet metal received was in as-rolled condition which has high strength and low ductility and strain hardening exponent. To bring the material in formable state needed heat treatment in vacuum. The distorted, dislocated structure resulting from cold working of aluminium is less stable than the strain free, annealed state, to which it tends to revert.

Table.2: Specification of laser cutting machine

Match type	CNC Laser cutting
Elect/voltage	440V,60Cy,3Ph
Maximum cutting dimension	80"x148"
Maximum cutting thickness	0.375 mild steel
Laser power	2600 watt
Laser gas	Co_2
X travel	1524mm
Y travel	3048mm
Z direction	101mm

Laser cutting

The Laser cutter works by directing a high powered laser beam very precisely at the chosen material to either etch the material or cut right through. The cutting beam is very thin (typically around 0.1mm) and precise resulting in incredibly detailed and accurate cuts. By reducing the beam power we can mark the surface of the material, this is known as etching or engraving and can give some stunning effects on materials.

Fig.1: Specimens obtained from laser cutting machine.

Determination of tensile properties.

The sub-sized specimens of AA1200 as per ASTM standard E8M were used for tensile testing. The rolling direction of the sheet was determined with help of stretcher roll marks. The specimens were prepared by laser cutting of annealed and as rolled aluminium alloy sheets in different directions relative to rolling direction (RD), i.e., 0° in RD, 45° w.r.t RD and 90° w.r.t RD. The specimens were tested in uniaxial tension on Instron machine. Load elongation data was obtained for all the tests which were converted into engineering stress strain curves. The standard tensile properties such as yield stress, ultimate tensile stress, uniform elongation and total elongation were determined from the stress- strain data.

Fig.2: Instron machine used for tensile testing

Determination of average plastic strain ratio (Normal anisotropy - R_{avg} value) and planar anisotropy-ΔR value.

The plastic strain ratio, which is a measure of anisotropy, was determined using specimens prepared according to ASTME517 specification. The specimens were elongated to predetermined longitudinal strain (15%depending on the % elongation up to UTS) and the testing was stopped before the onset of necking. Final width and gauge length were measured and the plastic strain ratio (R) is calculated as below [George E Dieter, Mechanical metallurgy].

$$\boldsymbol{R} = \frac{\mathcal{E}_w}{\mathcal{E}_t} = \frac{\mathcal{E}_w}{-(\mathcal{E}_w + \mathcal{E}_l)} = \frac{\ln \frac{w_f}{w_0}}{\ln \frac{l_0 w_0}{l_f w_f}}$$

W_0, l_0: initial width and length, W_f, l_f: final width and length

$\mathcal{E}_w$=true width strain

$\mathcal{E}_t$=true thickness strain

$\mathcal{E}_l$=true length strain

The R value was determined in three directions as mentioned in the tensile tests by repeating the above procedure. The normal anisotropy or average plastic strain ratio and planar anisotropy were calculated using the formula:

$$\mathbf{R_{avg}} = (\mathbf{R_0} + \mathbf{2R_{45}} + \mathbf{R_{90}})/4$$

$$\mathbf{\Delta R} = (\mathbf{R_0} - \mathbf{2R_{45}} + \mathbf{R_{90}})/2$$

R_0, R_{45} and R_{90} represent the R value in three directions.

LDH test of Al alloy sheets.

As suggested by Hecker [1974], samples were deformed using a hemispherical punch. The width was varied to obtain all possible deformation modes i.e. biaxial tension, plane strain tension and tension-compression.

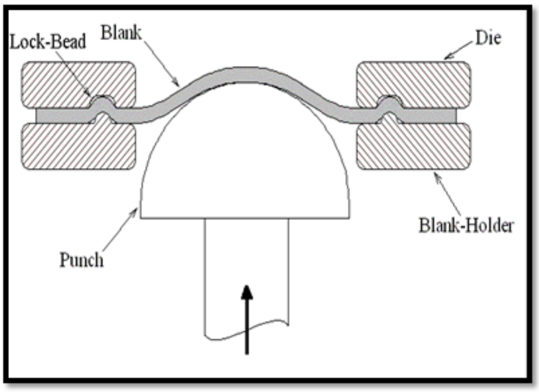

Fig.3: Schematic of punch and die setup for LDH tests

Microstructure of AA1200 (as rolled and annealed specimens)

Examination of the microstructure of aluminium and its alloys requires a well executed chain of steps carefully developed based upon scientific understanding and practical experience. In general, there are a series of steps required to prepare specimens: sectioning, mounting, grinding and polishing. In most cases, sectioning is required to obtain a small piece for examination. In a few cases, such as examination of fasteners, sectioning may not always be needed. Mounting, in some cases, may not be needed. After grinding and polishing, it is good practice to examine the surfaces before etching. For examination of intermetallic phases, it is common practice to etch with dilute aqueous HF solutions; a 0.5% concentration is very commonly used. This improves the image contrast and reveals little besides the intermetallic. Other etchants are used to detect segregation or cold work or reveal grain size. For some alloys, it is quite difficult to reveal the grain boundaries.

Finite Element Analysis

Computer based simulations are widely used by sheet metal engineers to meet the demand for better quality products. These simulations using finite element are used for predicting the failures, assessing a proposed forming process, designing tools and also in troubleshooting the manufacturing problems.

In the this work, the finite element simulation was carried out for the prediction of failure in stretch forming of aluminium alloys. The FE simulation was carried out in Abaqus 6.11, commercially available dedicated software for sheet metal forming applications. This system provides preprocessing (auto meshing, tool positioning, draw bead representation) and post processing (animation, formability plot, forming limit diagram). Default input parameters are generally chosen to give efficient, accurate simulation results. The FE simulations were done to check the accuracy of failure prediction in stretch forming of aluminium alloys. The failure predictions based on the developed as well as existing correlations were compared with the experimental results.

IV. RESULTS AND DISCUSSION

Tensile properties

Table.3: Tensile properties of as Rolled AA1200 (Thickness: 1mm)

Orientation wrt RD	YS(Mpa)	UTS(Mpa)	n	k	%elongation
0^0-1	77.6	97.6	0.298	312.9	9.94
0^0-2	67.4	75.5	0.098	117.6	7.13
0^0-3	68	72.2	0.072	103.7	7.27
45^0-1	47.2	52.7	0.072	71.8	6.85
45^0-2	62	69.5	0.09	103.2	6.09
45^0-3	93.2	104	0.423	596.4	7.84
90^0-1	91.4	104	0.0437	684.7	5.99
90^0-2	90.4	103	0.359	487.8	6.08
90^0-3	91.4	107	0.511	882.7	7.03

Table.4: Tensile properties of as Rolled AA1200 (Thickness: 1.6mm)

Orientation wrt RD	YS(Mpa)	UTS(Mpa)	n	k	%elongation
0^0-1	56.9	64.9	0.092	91.6	9.74
0^0-2	51.8	60.2	0.089	87.26	9.12
0^0-3	43.8	50.8	0.077	68.4	11.6
45^0-1	57.2	64.1	0.088	97	7.66
45^0-2	51.9	59.4	0.078	85.6	9.09
45^0-3	47.8	54.6	0.07	74.8	8
90^0-1	48	52.6	0.082	76.6	6.68
90^0-2	51.8	57.7	0.094	88.2	7
90^0-3	56.7	62.4	0.192	142.4	6.89

Table.5: Tensile properties of annealed AA1200 (Thickness: 1mm)

Orientation wrt RD	YS(Mpa)	UTS(Mpa)	n	k	%elongation
0^0-1	33.8	54.5	0.349	122.3	42
0^0-2	29.1	47.2	0.349	122.3	38.4
0^0-3	26.5	42.8	0.364	97.4	42.3
45^0-1	32.7	54.3	0.394	117.5	59.1
45^0-2	40.2	64.8	0.358	130.3	61.7
45^0-3	39	64.7	0.363	132.1	49.7
90^0-1	25.2	41.4	0.405	108.7	32
90^0-2	26.3	43.2	0.375	102.1	41.7
90^0-3	24.3	40.6	0.405	99.2	42.1

Table.6: Tensile properties of annealed AA1200 (Thickness: 1.6mm)

Orientation wrt RD	YS(Mpa)	UTS(Mpa)	n	k	%elongation
0^0-1	26.2	43.2	0.405	109	39.7
0^0-2	26.7	44.4	0.389	103.5	48.9

0^0-3	28.3	45.9	0.393	109.9	46.1
45^0-1	31.3	52	0.418	115.8	63
45^0-2	31.3	51.9	0.426	118	57.4
45^0-3	31.9	52.6	0.434	122.3	54.2
90^0-1	30.6	50.6	0.381	116.1	44.9
90^0-2	28.8	47.5	0.375	107.7	45.9
90^0-3	16.8	27	0.392	65	39.4

Anisotropy of annealed AA1200

Table.7: Annealed AA1200 (Thickness: 1mm)

Orientation wrt RD	W(i)	W(f)	GL(i)	GL(f)	ε_w	ε_L	ε_T	R
0^0-1	5.79	5.43	31.06	36.06	-0.06419	0.149263	-0.08507	0.75459
0^0-2	5.76	5.46	31.06	36.06	-0.05349	0.149263	-0.09577	0.558484
0^0-3	5.74	5.42	31.06	36.06	-0.05736	0.149263	-0.0919	0.624194
45^0-1	5.82	5.61	31.06	36.06	-0.03675	0.149263	-0.11251	0.326622
45^0-2	5.76	5.65	31.06	36.06	-0.01928	0.149263	-0.12998	0.148344
45^0-3	5.78	5.64	31.06	36.06	-0.02452	0.149263	-0.12474	0.19656
90^0-1	5.74	5.39	31.06	36.06	-0.06291	0.149263	-0.08635	0.728595
90^0-2	5.71	5.35	31.06	36.06	-0.06512	0.149263	-0.08414	0.773969
90^0-3	5.71	5.37	31.06	36.06	-0.06139	0.149263	-0.08787	0.69864

Table.8:" Annealed AA1200 (Thickness 1.6mm)

Orientation wrt RD	W(i)	W(f)	GL(i)	GL(f)	ε_w	ε_L	ε_T	R
0^0-1	5.71	5.44	31.06	36.06	-0.05194	0.149263	-0.09733	0.533629
0^0-2	5.72	5.44	31.06	36.06	-0.05368	0.149263	-0.09558	0.561606
0^0-3	5.8	5.48	31.06	36.06	-0.05157	0.149263	-0.0977	0.527829
45^0-1	5.73	5.57	31.06	36.06	-0.03354	0.149263	-0.11572	0.289856
45^0-2	5.71	5.57	31.06	36.06	-0.02832	0.149263	-0.12094	0.234164
45^0-3	5.79	5.57	31.06	36.06	-0.03528	0.149263	-0.11399	0.309485
90^0-1	5.73	5.34	31.06	36.06	-0.06524	0.149263	-0.08402	0.776461
90^0-2	5.7	5.37	31.06	36.06	-0.06314	0.149263	-0.08612	0.733152
90^0-3	5.68	5.39	31.06	36.06	-0.05767	0.149263	-0.09159	0.629695

Table.9: Values of R

Thickness	R_0	R_{45}	R_{90}
1mm	0.645756	0.223842	0.733735
1.6mm	0.541021	0.277835	0.713103

Table.10: Values of Anisotropy

Thickness	Normal anisotropy(R_{avg})	Planar anisotropy (ΔR)
1mm	0.456794	0.465904
1.6mm	0.452449	0.349227

Microstructure of AA1200

The results obtained from the microstructure test of AA1200 is shown blow.

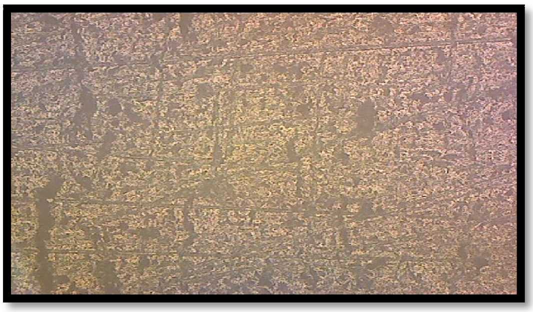

Fig.4: microstructure of annealed AA1200

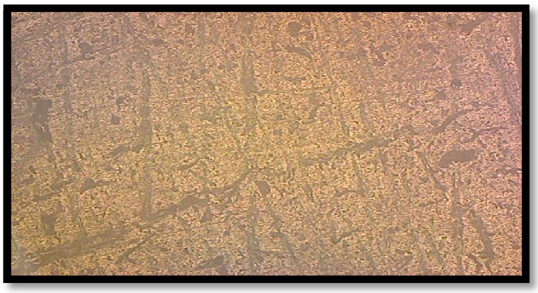

Fig.5: microstructure of as rolled AA1200

Microstructure of aluminium and its alloys can be prepared using a straight forward four or five step procedure. Always section specimens with an abrasive wheel developed for metallography to minimize the damage at the cut. Then, start grinding with the finest possible abrasive size that will remove the sectioning damage and get all of the specimens in the holder to the same plane in a reasonable amount of time. Keller's etch was found to be very useful for revealing the grain structure of aluminium alloys. It was more successful than any of the standard etchants.

LDH test of AA1200

Table.11: LDH test values of annealed AA1200 for different thickness

Failure points (1mm)	Minor strain	Major strain
1	0.073342	0.661675
2	0.092124	0.744198
3	0.09039	0.634173
Failure points (1.6mm)	Minor strain	Major strain
1	0.079043	0.635564
2	0.100723	0.819158
3	0.114481	0.661271
Safe points (1mm)	Minor strain	Major strain
1	0.086052	0.512572
2	0.093698	0.564837
3	0.084842	0.498685
Safe points (1.6 mm)	Minor strain	Major strain
1	0.102691	0.498895
2	0.092319	0.534202
3	0.100613	0.554041
Specimens	LDH(mm)thickness 1mm	LDH(mm)thickness 1.6mm
1	21.90	23.74
2	22.10	23.80
3	22.26	24.14

The limiting strain values and the formability of sheet metal were found to increase with increasing sheet thickness.

Finite element analysis results

As discussed in chapter 4, stretch forming of different type of specimens was simulated using ABACUS 6.11 to predict failure and LDH for the cases of biaxial stretching, plane strain condition and tension-compression. The LDH has been found to be 24.14 mm which is significantly higher LDH which means formability increases with the increases of thickness. There has been a significant improvement in accuracy of prediction of limiting dome height and limit strains in FE simulations. The blow figure explains the finite element analysis.

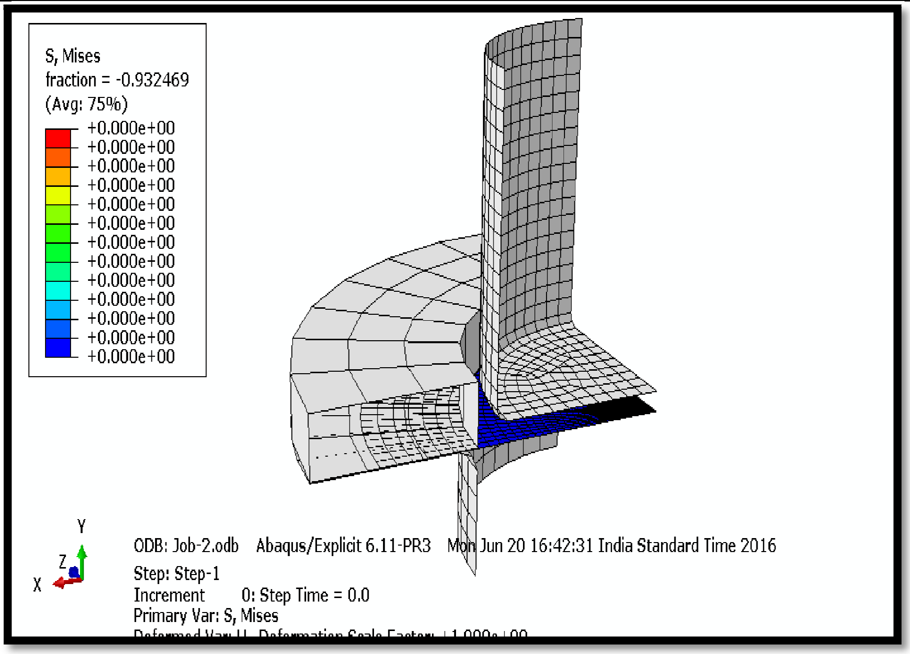

Fig.6: The schematic of the meshes assembly for FE analysis

V. CONCLUSIONS

Based on the results and discussions presented in the previous chapter the following conclusions are drawn:

1. The tensile tests showed a large variation in mechanical properties of the aluminium alloys used in this work due to the differences in thickness and annealing.
2. Most of the aluminium alloys specimens have high strain hardening exponent indicating good stretchability.
3. Anisotropy influences both mechanical and physical properties of metals. The value of the average plastic strain ratio for AA1200 is less than 1 indicates good drawability of AA1200 sheets. The value of planar anisotropy is almost found to be equal to the average plastic strain ratio.
4. Experimentally the value of planar anisotropy of aluminium alloys is always less than one.
5. Microstructure of aluminium and its alloys can be prepared using a straight forward four or five step procedure. Keller's etch was found to be very useful for revealing the grain structure of aluminium alloys. It was more successful than any of the standard etchants.
6. From the LDH test the limiting strain values and the formability of sheet metal were found to increases with increasing sheet thickness.
7. There has been a significant improvement in accuracy of prediction of limiting dome height and limit strains in FE simulations.

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