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Finite Element Analysis of Biaxial Stretch Forming of Very Thin Sheets

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ABSTRACT

The present work is aimed at studying formability of very thin sheets of low carbon steel and aluminum alloys in biaxial stretching using different tool dimensions. In this study, the relative punch diameter D_p/t (D_p is punch diameter and t thickness of blank) has been varied in the range 2 to 500 was used to represent the effect of the feature size. Thin sheets of aluminum alloy (AA) 6061 , AA 8011 of 500 µm and 200 µm thickness respectively and Low carbon steel of 250 µm thickness were used for simulation work. Finite element (FE) simulations have been carried out to study the failure strains and % thinning both in macro and micro-biaxial stretching with a hemi spherical bottom punch. FE simulation results show the relative punch diameter have significant effect on formability of these materials.

***Keywords*: FE simulation, relative punch diameter , failure strain, biaxial stretch forming.**

1.INTRDUCTION

In the recent years there has been a growing demand for micro technical products in various fields of science and engineering such as electronics, micro electro mechanical systems (MEMS), telecommunication, medicine, sensor-technology, optoelectronics and bio-technology, automotive industry etc. Among the micro manufacturing processes, micro metal forming is one of the most suitable and cost effective processes for mass production of micro metal parts because of its high production rate, low material scrap rate, near net shape production and superior mechanical properties. Micro forming is defined as the production of metallic parts by forming with at least two part dimensions in the sub-millimeter range (Geiger et al. 2001).This size effect due to miniaturization influences material flow and formability in micro metal forming processes. The plasticity theory and the know-how of conventional metal forming technology developed under macro scale cannot be directly applied to micro forming. Successful forming of metal micro-components also requires careful design of the process to make it suitable for uniform material flow, small-scale tooling and material handling capability. (Vollertsen et al. 2004, Engel and Eckstein 2002, Geiger et al. 2001).

Micro sheet metal parts are required for important applications such as micro-resonators, micro-surgical tools and devices, micro cups, micro lead frames, micro-transmission components etc. These micro parts are manufactured by micro sheet metal forming processes like micro deep drawing, micro stamping and micro blanking operation. In case of micro sheet metal parts, formability of the sheet metals is another important factor that should be taken into account when designing a forming process. This information is useful both for the producer and the user of the thin rolled products.

The determination of the FLD for very thin materials below 0.4mm is rarely described in the literature, so conditions for their determination are not clear. The influence of material thickness as well as the average grain size of the material according to its thickness may cause some specific problems. The flow stresses decreases with the increasing of the miniaturization. (Kals and Eckstein 2000), (Michel and Picart 2003), (Raulea et al. 2001). The size effect is a characteristic of macro geometry of the initial work piece (billet/blank) microstructure, surface topography and state of lubrication. When the process is scaled down, these remain unchanged and it leads to a different metal flow behavior compared to conventional forming processes (Messner et al. 1994).

2. EXPERIMENTAL WORK

2.1 Material and chemical composition

In this study, aluminum alloy 6061 of 500 µm thickness, AA 8011 of 200 µm thickness and Low carbon steel of 250 µm thickness sheets have been used.

The chemical composition of materials by weight % used in the present work has been analyzed by spectroscopy as per ASTM- E-1507and is given in Table 1.AS per the below table AA 6061 series alloys, magnesium and silicon are the major alloying elements and 8011 alloys have significant amounts of iron and silicon.

TABLE 1. Chemical composition of the material (by weight %)

Material/Element(%)	***Al***	***Cu***	***Mg***	***Si***	***Fe***	***Ni***	***Mn***	***Zn***	***Sn***	***Ti***	***Cr***
AA6061	96.95	0.201	0.92	0.81	0.54	0.011	0.11	0.203	0.006	0.037	0.195
AA8011	reminder	0.026	0.01	0.64	0.742	0.003	0.03	0.006	0.005	0.01	0.001
Material/Element(%)	***Fe***	***C***	***Si***	***Mn***	***su***	***P***	***Ni***	***Cr***	***Mb***	***Al***	***Cu***
Low carbon steel	99.49	0.048	0.015	0.31	0.012	0.02	0.02	0.01	0.012	0.072	0.008

2.2.Mechanical properties

The specimens as per ASTM standard E8M (ASTM Standard, 1999) were used in the tensile testing of all three materials. The specimens were prepared by laser cutting in three directions with the length parallel (0^0), diagonal (45^0) and perpendicular (90^0) to the rolling direction of the sheet. The specimens were tested in uniaxial tension on Instron machine of at a constant cross head speed of 5 mm/min. Load elongation data was obtained for all the tests which were converted into engineering stress strain curves.

The plastic strain ratio, which is a measure of anisotropy, was determined using specimens prepared according to ASTM E517 specification. The specimens were elongated to 15% longitudinal strain. Final width and gauge length were measured and the plastic strain ratio (*R)* is calculated as per equation(1) (Dieter G. E, 1988).

$$R = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\varepsilon_w}{-(\varepsilon_w+\varepsilon_l)} \tag{1}$$

where, ε_w =true width strain, ε_t =true thickness strain, ε_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 ($\bar{R}$) or average plastic strain ratio was calculated using the equation (2).

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

R_0, $R_{45}$and R_{90}represent the R value at 0^0, $45^0$and $90^0$to rolling direction respectively.

2.3 Grain size

The microstructures of the materials in the as-received condition were studied using optical microscopy on the surface. The micro structure of material used for determining grain size which is used for analyzing the effect of thickness to grain size (*t/d*) ratio.

2.4 Stretch forming test

The biaxial stretch forming tests were done according to the procedure suggested by Hecker (1974). Tooling sets of hemispherical bottom punch of 101.6mm for AA6061material and 50mm punch diameter for low carbon steel were used. Experiments were conducted on a double action 100 ton hydraulic press. Three square specimens of size 175mm X 175mm from AA6061 material and 80 mmx80 mm from low carbon steel sheet were laser grid marked with 5 mm diameter circles for measuring the strain distribution in the samples after deformation. The experiments were stopped when a visible neck or initiation of fracture was observed on the specimens as shown in Figure 1. Major and minor principal strains were calculated by measuring major and minor diameters of ellipses on the deformed samples. A traveling microscope having a least count 1µm was used to measure major and minor diameters of ellipses for strain calculations.

3. FE SIMULATION PROCEDURE

In the present work, finite element analysis of biaxial stretch forming of three thin sheet metal blanks was carried out using the software Dynaform 5.8 with LSDYNA 971.

A hemispherical bottom punches of diameter (*Dp*) 101.6 mm, 50mm, 5 mm and 1 mm and the corresponding dies(lower die and blank holder) was modeled for FE simulation. In this study, the relative punch diameter D_p/t (D_p is punch diameter and t thickness of blank) has been varied in the range 2 to 500 as shown in Table 2, these were used for biaxial stretch forming simulation.

Tools (hemispherical punch, die and blank holder) were modeled as rigid bodies to avoid deformation of the tools during stretch forming. In the present work, Belytschko-Tsay thin shell elements were used for the blank and tools because of lower computational time. The number of thickness integration points was selected as 7 for better formability analysis. Adaptive mesh generation methodology was used in simulations to obtain greater accuracy. In this method, the elements are subdivided in to smaller elements wherever an error indicator shows that subdivision of elements will provide improved accuracy (Hallquist, 2006).

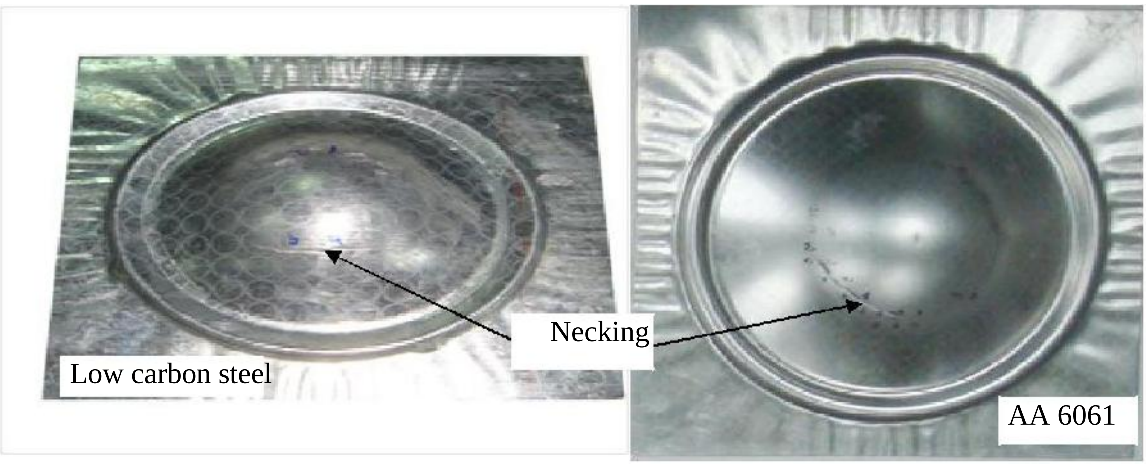


FIGURE 1. Deformed samples in biaxial stretch forming

The number of elements in the mesh, which depends on the blank size and element sizes are kept nearly equal for various relative punch diameters in the present simulation work. The blank was considered as a deformable body with appropriate yield criterion and stress-strain relation during non-linear plastic deformation to account for strain hardening. The yielding behavior of the blank material was considered as per Barlat's three-parameter plasticity model. This model incorporates the effect of both normal and planar anisotropy in polycrystalline sheet during deformation. The anisotropic yield function is defined as:

$$f = a\,|K_1 + K_2|^M + a\,|K_1 - K_2|^M + c\,|2K_2|^M = 2(\bar{\sigma})^M$$

$$\text{where, } K_1 - \frac{\sigma_{xx} + h\sigma_{yy}}{2} \text{ and } K_2 = \sqrt{\left(\frac{\sigma_{xx} - h\sigma_{yy}}{2}\right)^2 + \rho^2\sigma_{xy}^2} \qquad (3)$$

The coefficients in equation (3) a, c, h and ρ are calculated using anisotropic parameters R_0 and R_{90} (Barlat and Lian, 1989). M is Barlat's yield exponent and it was suggested that, for body centered cubic (BCC) materials, the most suitable value is 6 and for face centered cubic (FCC), the value is 8. These values are used in the present work. Both the dependence of yield stress on grain size and the strain hardening laws for polycrystalline materials have to be taken into consideration for reliable material models which is necessary for accurate analysis of micro-forming. In this formulation actual material flow curve (experimentally determined) was given as input . A typical FE model of the tools and the blank used for simulation of stretch forming is shown in Figure 2.

TABLE . 2 Ratio of punch diameter to sheet thickness (D_p/t)

Punch Diameter D_p(mm)	**Relative punch Diameter (D_p/t)**		
	***t* =0.5mm (AA 6061)**	***t* = 0.2mm (AA 8011)**	***t*=0.25mm (low carbon Steel)**
101.6	203.2	508	406.4
50	100	250	200
5	10	25	20
1	2	5	4

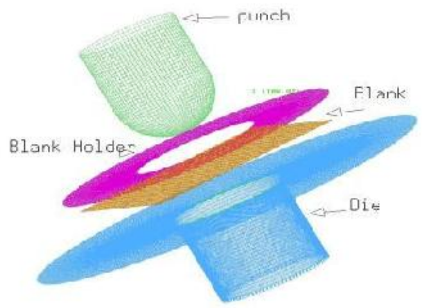


FIGURE 2 .Tooling in FE simulation

A circular draw bead was created in the die for constraining the material flow from the flange. Define the full lock draw bead force, the value calculated by empirical formula. The restraining force was calculated as per the draw bead geometry and this restraining force was given on the die as a boundary condition. When the blank slides in to the die, it experiences that restraining force and hence gets stretched instead of drawing in. A few trial simulations were done to identify the minimum required blank holding force to completely eliminate drawing in. The blank holder force was used in the range of 240N to 370 KN for smallest to biggest punch diameter.

The Coulomb friction law was assumed for all contacts, friction coefficients of 0.125 between the tool parts and the deformed sheet material was used (Ghosh, 1977).The die and blank holder were considered fixed entities andthe punch was moved down with a velocity equal to 1000 mm/sec in negative Z direction, where as in actual experiments, the punch velocity was 2mm/sec. This was done to reduce the simulation time. As the effect of strain rate has not been considered in defining the deformation behaviour of the materials, this would not affect the simulation results. The punch motion was considered using a trapezoidal profile. Total simulation time is divided into 30 time steps. The results of above simulations are analyzed and discussed as follows.

4. RESULTS AND DISCUSSION

The standard tensile properties such as 0.2% offset yield strength (*YS*), ultimate tensile strength (*UTS*), total % elongation, strain hardening exponent (*n*) and strength coefficient (*K*) were determined from the stress- strain data. A typical true stress–strain curve is shown in Figure 3 for each material which was used as input in this formulation.

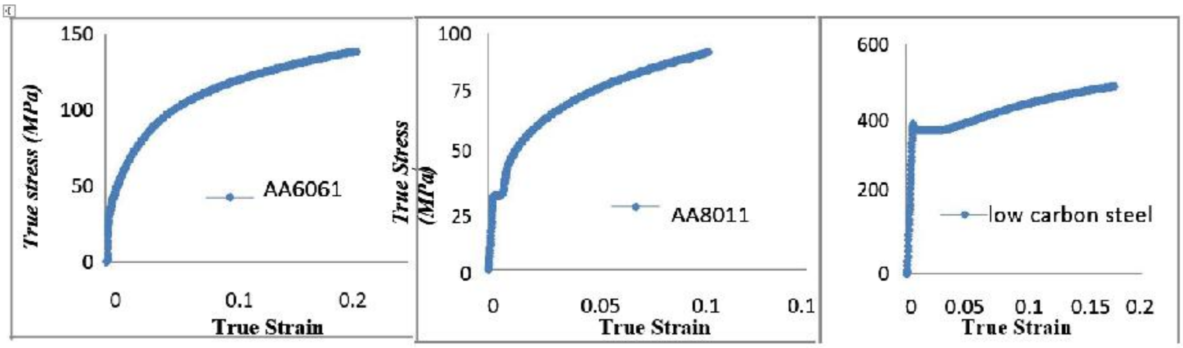


FIGURE 3. STRESS STRAIN CURVE

Mechanical properties of these three materials obtained from standard tensile tests are reported in Table 3 and these properties were used in all FE simulations.

TABLE 3.Mechanical properties of sheet materials.

Material and Thickness	*YS* N/mm^2	*UTS* N/mm^2	% Elongation	*n*	*K* (MPa)	Anisotropy parameter R_0	R_{45}	R_{90}	$\bar{R}$
AA 8011	35.9	90.8	16.4	0.28	179	0.70	0.59	0.64	0.63
AA 6061	45.8	113.7	23.4	0.30	235	0.70	0.63	0.65	0.65
Low Carbon steel	381.4	425.9	18.9	0.18	686	1.16	1.02	1.33	1.21

Figure 4 shows the micro structures of materials used for determining the thickness to grain size (*t/d*) ratio which is an important parameter. The thickness to grain size ratio (*t/d*) are found to be 15, 20 and 50 for low carbon steel, AA8011 and AA6061 respectively.

Low carbon steel (500x) **AA6061 (200x)** **AA8011 (400x)**

FIGURE 4. Microstructure of materials used in present work

A summary of the effect of *N* (*t/d)* on the flow stress based on the findings reported in the literature is presented in Figure 5 (Mahabunphachai and Koç 2008). The decreasing flow stress with the increasing miniaturization is also related to the ratio of sheet thickness to grain size (t_0/d) is an important parameter for flow behaviour in case of thin sheets, as shown in figure 3. For a given grain size as t_0/d decreases, flow stress decreases. The properties and grain size are almost same for both AA8011 and AA6061 material. But the failure strain of AA6061 are higher than that of AA8011 due to its higher t/d ratio.

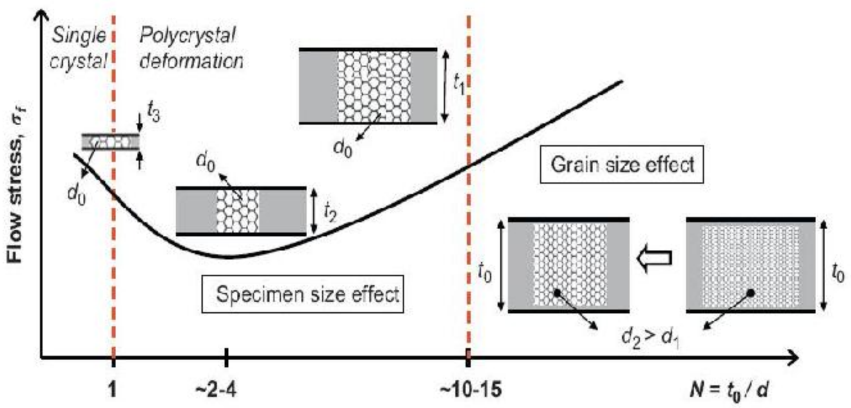
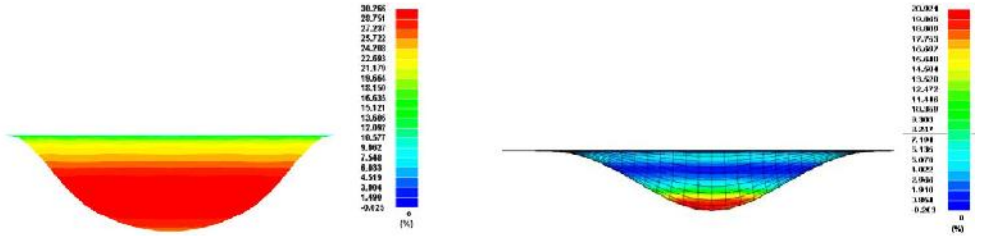


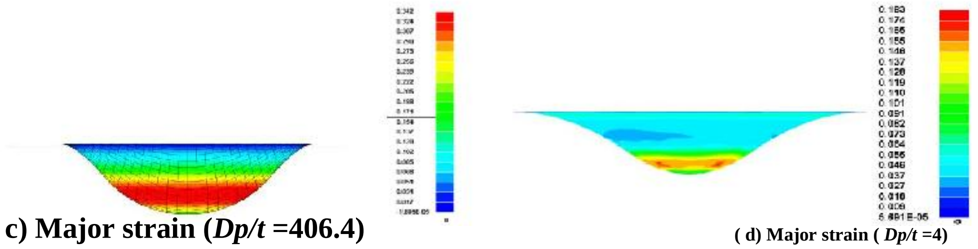
FIGURE 5. Grain v/s specimen size effect on the flow stress as function of N

Some results of biaxial stretch forming simulations for different values of *Dp/t* in the range of 2 to500 are shown in Figure 6. The first appearance of failure/necking was used for determining the failure strain (major and minor strain) and %thinning in the postprocessor of Dynaform. Experimentally determined forming limit diagram were used for prediction of failure. The FE simulation results are plotted in figure 7 for the variation of *Dp/t* ratio. In general it has been observed that as *Dp/t* ratio decreases the failure strain (both major and minor strain) also decreases as shown in Figure 7. This is clearly due to the feature size effect. As miniaturization of punch increases the area of deformation decreases and frictional forces become more predominant. The non uniformity of stress distribution increases causing lower forming limits. The maximum possible thinning in the deform region also reduced with *Dp/t* ratio in the case of all materials.



(a) % Thinning (*Dp/t* =200)

(b) % Thinning (*Dp/t* =2)



(c) Major strain (*Dp/t* =406.4)

(d) Major strain (*Dp/t* =4)

FIGURE 6. FE simulation in biaxial stretch forming for various *Dp/t*ratio

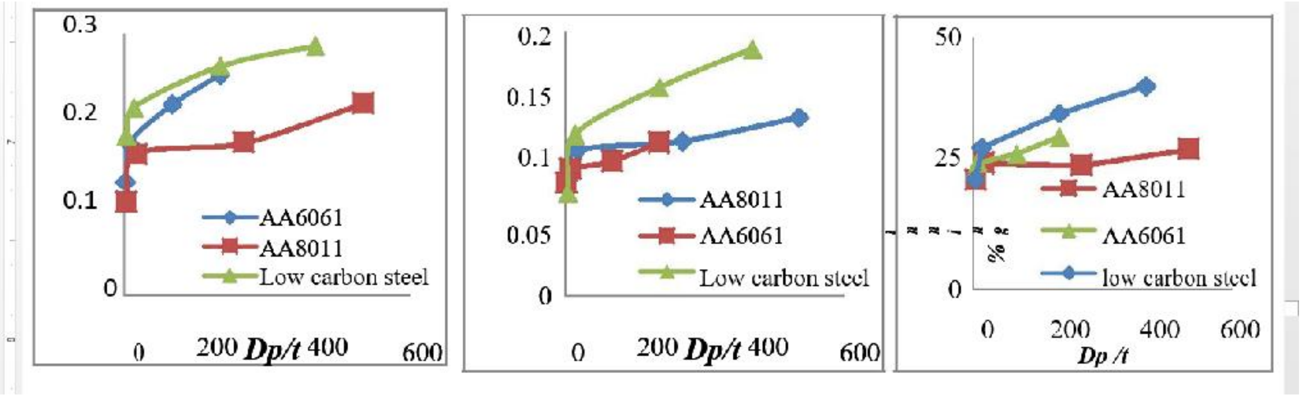


Figure 7. Effect of variation on Dp/t on failure strain and % thinning

Experimental validation of simulation results is in progress. Biaxial stretch forming experiments have been conducted for Dp/t ratio of 200 for AA6061 and low carbon steel and results are compared with simulation results which are reported in Table 4. These provisional experimental results shows good agreement with simulation values. Development of ultra precision Micro press for the micro metal forming that has desktop size which can perform various processes, i.e. micro- extrusion, punching of micro holes, micro deep drawing and micro bending is under progress to carry out the experiment in micro forming.

TABLE 4. Experimental and simulation value of major and minor strain

Material	Experimental value		Simulation Value	
	Major strain (%)	Minor strain (%)	Major strain (%)	Minor strain (%)
AA6061	25.34	9.14	27.5	11.6
Low carbon steel	27.70	13.2	28.3	15.8

5. CONCLUSION

From the FE simulations carried out on biaxial stretch forming of three thin sheet materials, the following conclusions can be drawn. The punch diameter to sheet thickness ratio has a significant effect on formability. As *Dp/t* ratio decreases, failure strain decreases for all the three materials. Maximum % thinning also decreases withdecrease in *Dp/t* ratio. In case of macro forming, the experimental and simulation results showed good agreement. Development of a micro press and micro tooling to carry out micro forming experiments is in progress.

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