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Hardness Effect of Polyurethane Rubber on Mesoscale Rubber Pad Forming

Mahmut Tandogan[1], **Omer Eyercioglu**[2]

Research Assistant, Department of Mechanical Engineering, Gaziantep University, Gaziantep, Turkey[1]

Professor Doctor, Department of Mechanical Engineering, Gaziantep University, Gaziantep, Turkey[2]

Abstract: Mesoscale parts are the parts whose two dimensions are in the range between 0.1 and 10 mm. Owing to the increasing demand on miniaturized devices or machines, requires the production of miniaturized pats. Mainly, mesoscale parts are utilized in electronic devices, aircraft industry, and defense industry. Because of small dimensions, conventional type of forming is difficult and can be expensive. In this study, meso/miniature forming with flexible die was investigated numerically and experimentally. Dome shape was studied for aluminum 1100 H14 sheet as a workpiece using polyurethane rubber as flexible material. The analyses were carried out for polyurethane rubber with two different hardness values (60A and 80A Shore) and for the conventional (metal to metal) forming process. Also, experiments were conducted to verify the finite element analysis (FEA) results. The results show that tearing in conventional forming was prevented by using flexible die. The process is applicable for forming of mesoscale parts without excessive thinning. Also, the harder polyurethane is better to get desired final geometry than the softer one.

Keywords: Finite element, Flexile die, Mesoscale, Rubber pad, Sheet metal forming.

I. INTRODUCTION

In sheet metal forming process, the geometry of sheet metal follows the geometry of die. Flexible tools are used to push the sheet part for flexible forming. The flexible material is utilized to obtain uniform pressure distribution on all formed sheet metal surfaces as it is formed to geometry of die block [1]. In this type of forming, a flexible medium such as rubber, fluid or highly-viscous semi-solid material is replaced with classic rigid dies, to form a part into its final shape [2].

Polyurethane rubber has significant properties among other flexible mediums. Thiruvarudchelvan [3] have investigated the role of urethanes that are considered to be the best material for tools for flexible die forming in this review. It is concluded that urethanes have good oil and solvent resistance, good wear resistance, high thermal stability and load bearing capacity. Due to these properties, urethane was considered to be appropriate material for flexible forming. Sala [4] studied the Guerin flexible forming process of 2024 aluminum alloy part using own made finite element code. This part is utilized in the construction of fuselage frame of AerMacchi MB-399 training aircraft. Different effects, such as stamping velocity, component shape, specimen heat treatment type, and elastic material thickness were examined. His study shows effects of these parameters on the forming defects and reducing set-up times.

Also, he concluded that rubber pad thickness and bending radius are the main parameters on forming. Dirikolu and Akdemir [5] studied the effect of rubber material hardness and workpiece material type on stress distribution using a commercially available finite element package(ANSYS) simulation study related the rubber pad forming process. Simulations were conducted with appropriate nonlinear material for blank, hyperplastic material and friction between them. Advancement and hardness of rubber pad, blank material type and effect of friction between contacts surfaces are important parameters associated with flexible forming process. They show that the use of finite element software is the easy way to determine the process parameters concerning with the flexible forming process before actual experiment. The investigations stated that variation of pad thickness would not make a remarkable change on forming stress in the blank.

Del Prete et al. [6] presented numerical simulation of the rubber pad forming process of the use of aluminum alloy as a workpiece material for aeronautic component. Some effects, depending upon stamping strategy, formed part geometry and rubber pad characterization was taken in account. This study is capable to produce shallow formed parts with a less metal thinning. Based on the FE analysis, the minimum available fillet radii for aluminum sheet have been found in term of the proposed measure. To decrease the minimum concave fillet radius, the fillet radius of the punch should be increased. A rubber hardness effect on the blank deformation becomes prominent when the concave radii increase. Jenn-Terng Gau et al. [7] studied the influence of size effects on micro channel forming experimentally with channel widths not bigger than 1 mm. They used the aluminum thin sheets (75 and 50 μm), aluminum foils, with annealed different temperatures and polyurethane with two different (40A and 90A shore hardness) hardness values. By applying different annealing operations, sheets gained the different grain sizes, thus thickness and average grain size ratio, T/D, was obtained. By using this ratio as a parameter, influence of model of size in two models were proposed. The deeper micro channel was obtained the softer polyurethane according to experiments. Also it is concluded that annealed at a higher temperature sheets has better formability for flexible die forming process.

In this study, rubber pad forming was carried out by means of Guerin process for mesoscale. Some device or machine parts have small sizes. In manufacturing, dimensions can be classified as micro, meso or miniature and macro dimensions. Meso/miniature scale manufacturing is process of creating products with dimensions in a range of approximately from 0.1 mm to 10 mm. Meso manufacturing processes are filling the gap between macro and micro manufacturing processes and overlaps both of them. Mesoscale forming stands for the plastic deformation process to produce parts with two dimensions in range of 0.1-10 mm [6]. Polyurethane rubbers with 60A and 80A shore hardness, aluminum 1100 were utilized as flexible medium and workpiece, respectively. The final shape geometry, effective stress distribution and required load for forming operation were investigated. Also conventional forming type was studied to find out the effect of rubber on forming operation.

II. EXPERIMENTAL STUDY AND FINITE ELEMENT MODELLING

A. Workpiece Material

Aluminum sheet (Al 1100) with 0.5 mm thickness was used as workpiece material in experiments and numerical analysis. Because, this material is widely used for miniature parts in electronic devices, aircraft industry, and defence industry. The chemical composition of the workpiece material is given in Table 1.

TABLE 1 Chemical Composition of Al 1100 Alloy [8]

Si	**Mn**	**Cu**	**Fe**	**Zn**	**Al**
0.00-0.095	0.00-0.05	0.05-0.20	0.00-0.095	0.00-0.10	Balance

Fig. 1 Aspects of Aluminum Specimens after Tensile Test

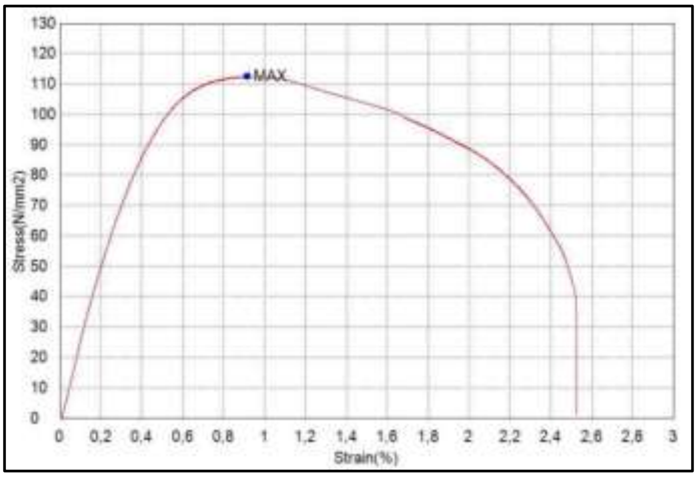

Fig. 2 Obtained Stress-Stain Curve from Tensile Test

Tensile properties of this material are obtained from tensile test. Tensile test were conducted on dog-bone shaped specimens in SHIMADZU AG-X machine. The specimens were 175 mm length and 30 mm wide with 50 mm gauge length. Test was carried out 1 mm/min of strain rate. The aspect of some specimens after tensile test is shown in Fig. 1. The yield strength of 75±5 MPa is measured along longitudinal direction by using offset yield method in Fig. 2.

B. Flexible Material

Polyurethane rubber is the one of the elastomer materials. Elastomers are generally exposed to large deformation. However, in our study deformation is relatively small. So, if modulus of elasticity, E, is known, rubber design problems for this small deformations can be solved [2]. Polyurethane materials with 60 and 80 shore A hardness which are measured by using shore A durometer, shown in Fig. 3, were utilized for flexible material to determine the effects of rubber in this study.

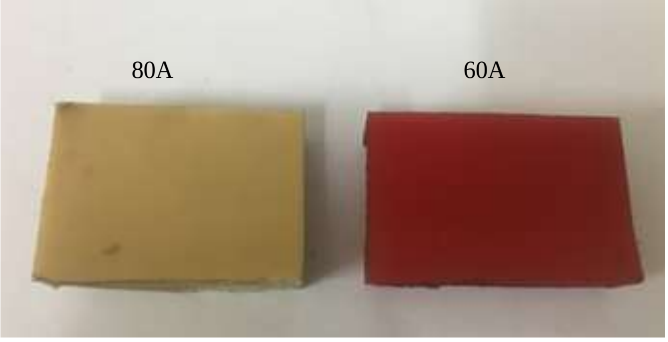

Fig. 3 Polyurethane Materials

Compressive stress-strain curve of the flexible material must be obtained to provide the experimental results the uniaxial compression test can be conducted. However, the effect of shape factor should be taken into account. Shape factor can be defined as ratio of one loaded surface area to total area of unloaded surfaces. Parts made from the same compound and having the same shape factor behave identically in compression, regardless of actual size or shape [2].

So, shape factor for solid discs and cylinders as in Equation (1) is:

$$\mathrm{SF} = \frac{\mathrm{d}}{4\mathrm{h}} \quad (1)$$

where d is the diameter of the disc or cylinder and h is the height of the disc or cylinder. Taking the shape factor into consideration, compressive stress-strain curves are shown in Fig. 4 and Fig. 5, respectively.

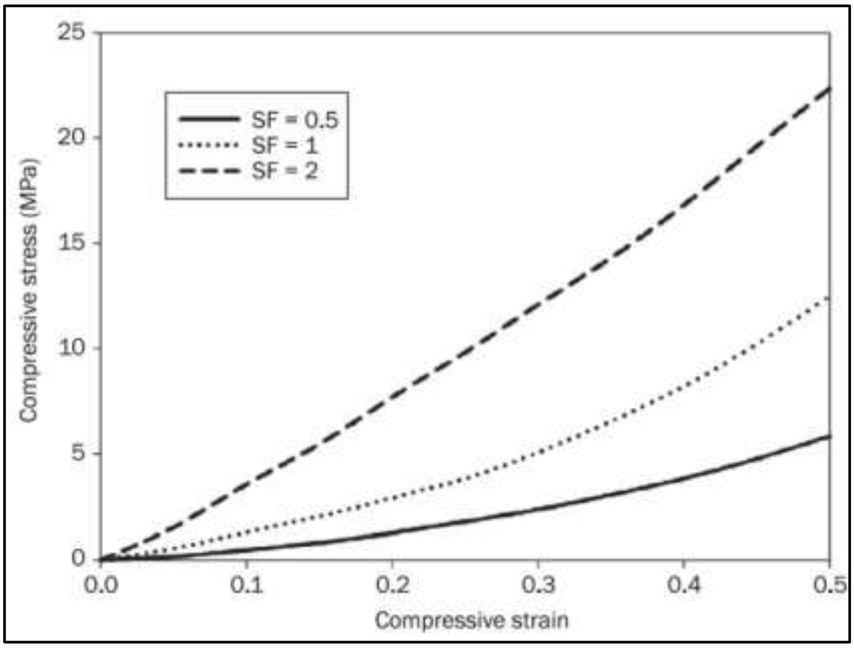

Fig. 4 Compressive Stress–Strain Curves of 60A Polyurethane with Different Shape Factors [2]

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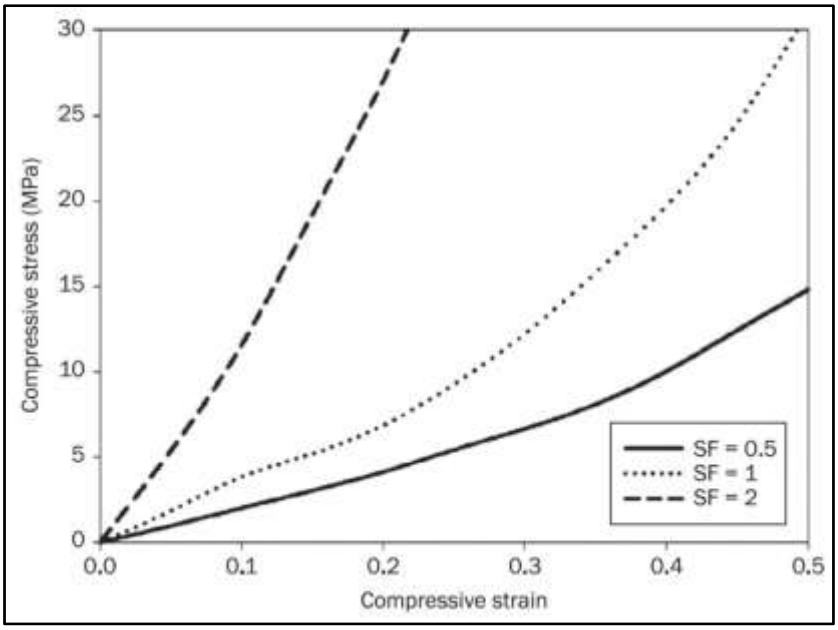

Fig. 5 Compressive Stress–Strain Curves of 80A Polyurethane with Different Shape Factors [2]

Also used polyurethanes have the properties in Table 2 [2].

TABLE 2 Polyurethane Properties [2]

Polyurethane Hardness	Thermal Expansion	Poisson's ratio
60A	57.6 x 10^{-6} m/mK	0.4997
80A	57.6 x 10^{-6} m/mK	0.4995

C. Experimental Setup

Dome shape die set was used as a geometry schematically shown in Figure 6. In experimental study, 0.5 mm Al 1100 sheet was used as a workpiece material and 60A shore polyurethane rubber was used as a flexible material to perform experiments. Experimental setup for dome shape is shown in Fig. 7.

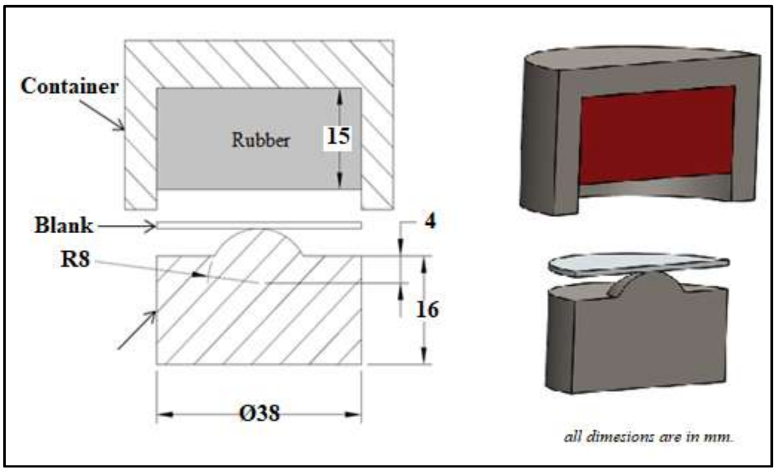

Fig. 6 Schematic Representation of Dome Shape Die Set

The apparatus used in these experiments was built around a servo controlled press machine (constructed in Mechanical Engineering Department), with the maximum capacity of 20 kN (shown in Fig. 8). The experiment begins with the die placed on the base of the press machine and then the aluminum blank is introduced between the die and the flexible punch, also SEA 40 oil was used as a lubricant. After this, the forming operation was carried out with 1 mm/min stroke rate. During the experiment, the force on the die produced by flexible punch was measured by load cell of type Keli LFSC-A with capacity 50 kN, manufactured by Keli Sensing Technology (Ningbo) Co. Ltd., China.

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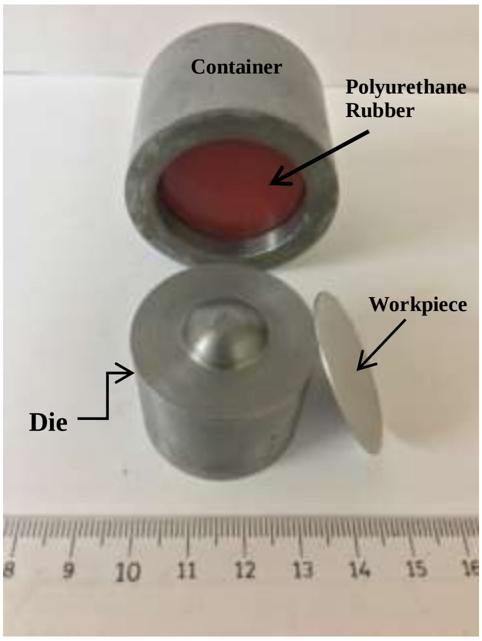


Fig. 7 Dome Shape Die Set

Fig. 8 Servo Controlled Press Machine

D. Finite Element Modelling

FEM was created for dome shape and finite element analysis was conducted in DEFORM™ 2D. Also conventional forming (without flexible material) was applied to investigate the formability improvement. DEFORM™ 2D is the one of the commercial finite element software packages and has been used in this study. The conventional forming model in FE analysis include the three main elements, male die, female die and blank in Fig. 9.

The die and container were modeled as a rigid body, because the stress and strain of the die were not analyzed. Due to this any material is not attached and mesh was not created in DEFORM for rigid bodies. This is usable application to reduce the running time in simulations.

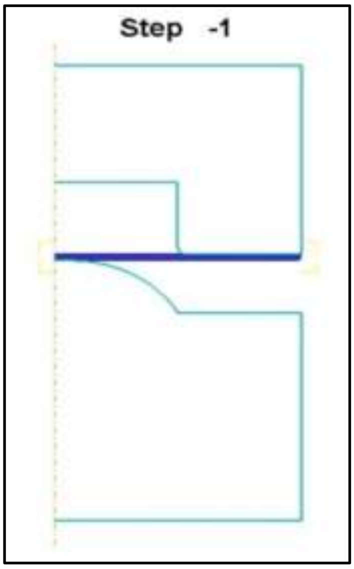


Fig. 9 Conventional Forming (Metal to Metal Contact) Model of Dome Shape

The blank material was modeled as elasto - plastic material. AL 1100 with 0.5 mm thickness material was selected from DEFORM database, the flow stress – strain curve was obtained in library of DEFORM, it is coincided calculated flow stress - strain curve after conducted tensile test, is shown in Fig. 10 and elastic modulus E of 70 GPa and Poisson ratio of ν is 0.33. Normalized Cockroft & Latham (1968) was chosen as the fracture criterion. The critical damage factor value, C, can be evaluated by a tensile test and does not depend on working operation. And damage factor for Al 1100, taken from tensile test, is defined as 0.34 as a Normalized C&L. If it is defined, it means that material starts to fracture [9] when reaching of defined value.

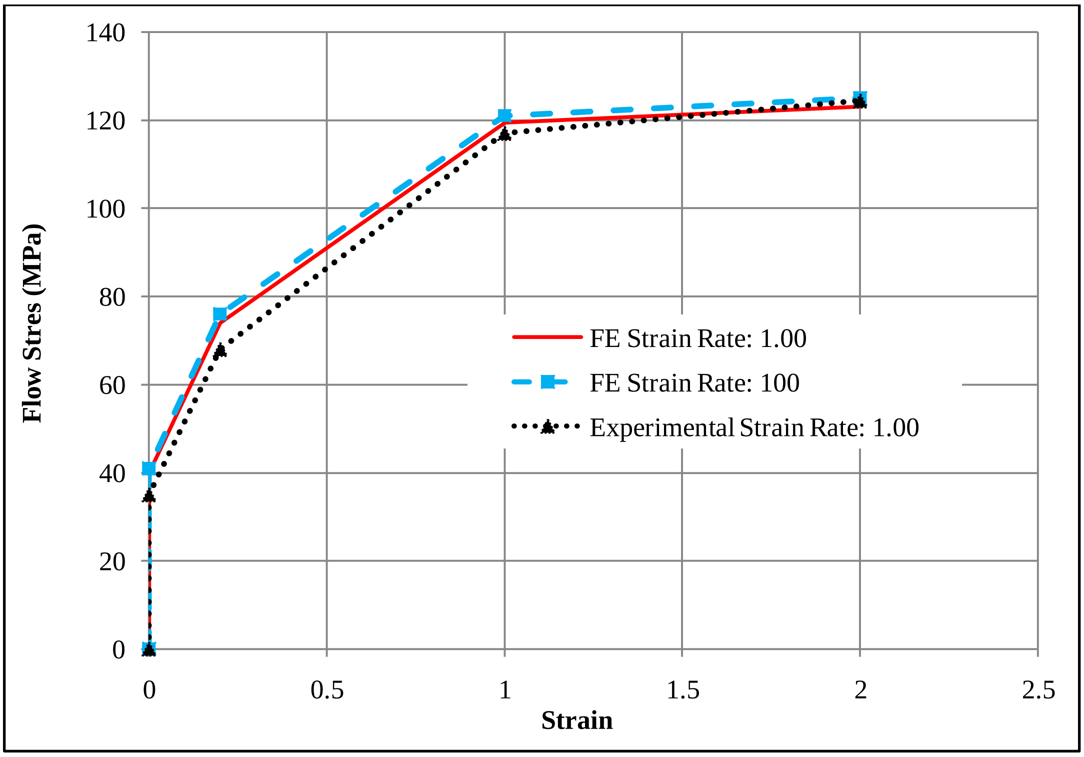


Fig. 10 Flow stress – Strain Curve of AL 1100

The flexible material was created in DEFORM by using polyurethane properties in Table 2. Also, compressive stress – strain curve was obtained from uniaxial compression test of polyurethane in Fig. 4 and Fig. 5. Then shape factors are calculated by using equation 5.6 for dome shape gives 0.5. So, young’s modulus’s was obtained by applying Hooke’s Law from Fig. 4 and Fig. 5 are shown in Table 3.

TABLE 3 Young's Modulus Values of Flexible Materials

TYPE	Young's Modulus, MPa	
	60A	80A
Dome Shape	11	20

Also, there are frictions at interfaces between flexible material - die, flexible material - blank and blank - die. These frictions were assumed to follow Coulomb's model [10, 11]. The friction coefficients at the rubber-container, rubber-blank and blank-die were considered to be 0.2 and 0.1 respectively [10, 11, and 12]. Table 4 shows the specifications of the contact regions. Frictions in conventional forming are shown in Table 5.

TABLE 4 Frictions in Contact Regions of Flexible Forming

Parts in contact	**Friction value**
Rubber and Container	0.2
Rubber and Blank	0.2
Blank and Die	0.1

TABLE 5 Frictions in Contact Regions of Conventional Forming

Parts in contact	**Friction value**
Blank and Male Die	0.1
Blank and Female Die	0.1

For rubber material and blank material, nodes and elements is shown in Table 6 and for conventional forming nodes and element number of blank is given in Table 7 are generated by meshing in modelling.

TABLE 6 Elements and Nodes for Flexible Forming in FEM

TYPES	**Blank**		**Flexible Material**	
	Elements	**Nodes**	**Elements**	**Nodes**
Dome Shape	1790	2051	9851	10050

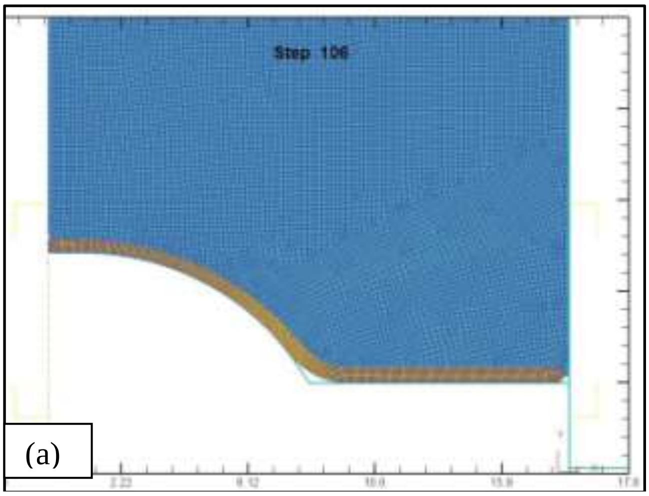
TABLE 7 Elements and Nodes for Conventional Forming in FEM

TYPES	**Blank**	
	Elements	**Nodes**
Dome Shape	1790	2051

III. RESULTS AND DISCUSSION

A. Finite Element Results

The final shape of workpiece by using 60A rubber, 80A rubber and conventional forming after simulations are shown in Fig. 11 (a), (b) and (c) respectively.



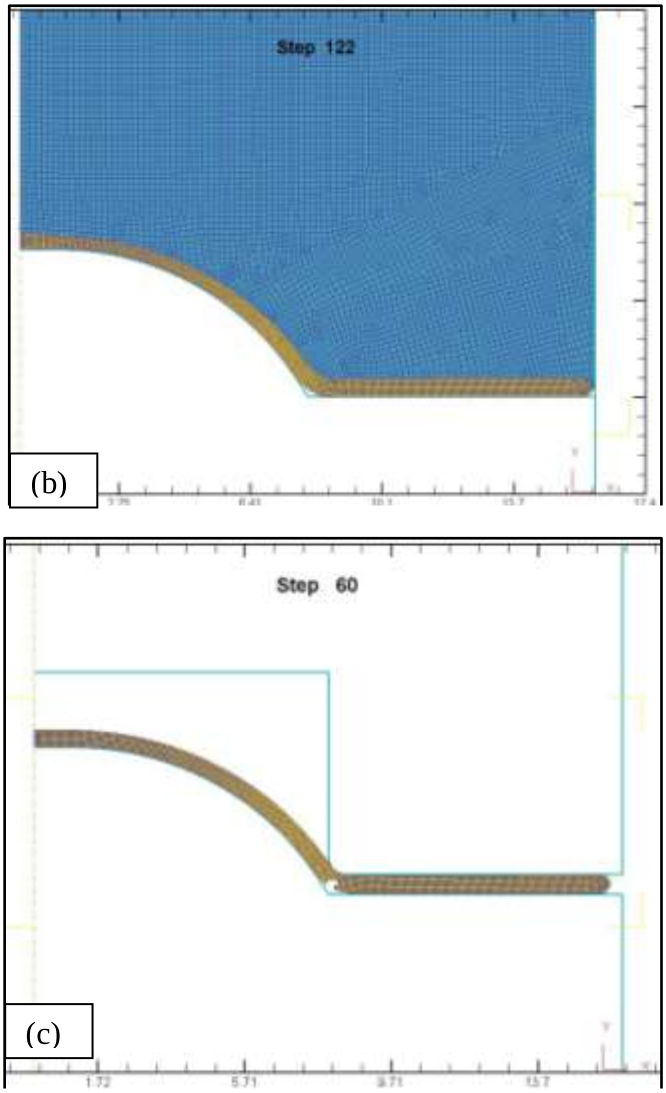


Fig. 11 Final Dome Shapes after Simulations (a) 60A Hardness Rubber, (b) 80A Hardness Rubber and (c) Conventional Forming

So, it is easily seen that little gap occurred between geometry of die and blank for rubber pad forming. The gap area of 60A and 80A rubber forming was calculated as nearly 0.291 mm2 and 0.08 mm2 by means of summation of two triangles areas in Fig. 12 (a) and (b) respectively.

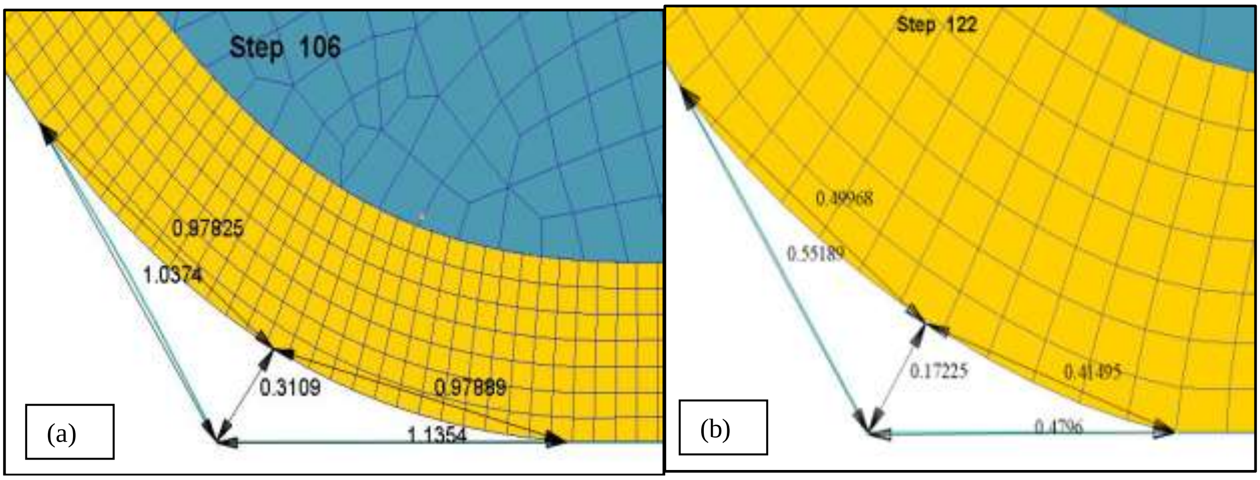


Fig. 12 Gap Areas of Dome Shape Flexible Forming for (a) 60A Forming and (b) 80A Forming

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Harder polyurethane gave the less gap area against the softer one. Additionally, gap area of conventional forming cannot be calculated due to tearing of sheet. Tearing or fracture occurred when damage factor reaches the defined value. This is probably occurs on the area high effective stress distribution. Effective stress distribution is illustrated in Fig. 13 (a), (b) and (c) for 60A, 80A and metal to metal die forming (conventional) respectively. The maximum effective stress value 39.1 MPa and 44.1 MPa for softer and harder polyurethanes respectively. Also, maximum effective stress distribution has obtained throughout areas where more thinning observed.

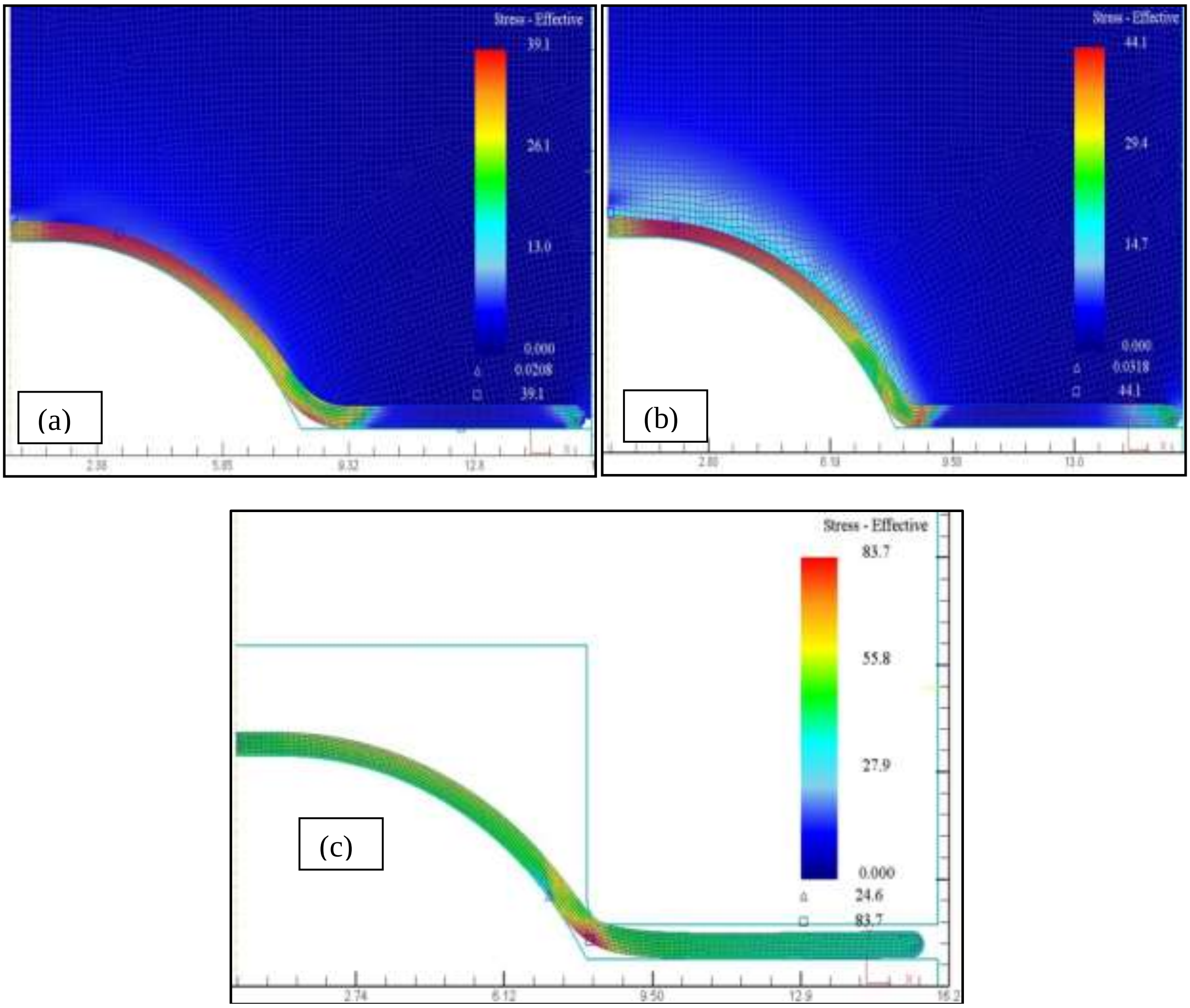

Fig. 13 Effective Stress Distributions on (a) 60A Flexible Forming, (b) 80A Flexible Forming and (c) Conventional Forming

Fig. 13 (c) shows the effective stress distribution of conventional forming before fracture stars. The maximum effective stress value of 83.7 MPa was occurred on the area of tearing. This value is nearly twice of the value of 80A rubber pad forming. This condition may be main reason of tearing problem in conventional forming. Because in flexible die forming, polyurethane rubber contacts the all surface of the workpiece material and pressure exerts more uniform throughout sheet metal surface.

However, in conventional forming metal die contacts partially and all forming load exerts small area compared to flexible die forming process. This may increase the occurred effective stress.

For forming dome shape, harder polyurethane has given the best formation. However, load required to form this shape was obtained as biggest load between them. Maximum loads occurred as 13442.8 N for 80A polyurethane and 6476 N for 60A polyurethane, nearly harder's twice of softer's load. In conventional forming, load at fracture starts point was taken as 962 N. This load is so small compared the flexible forming. However, giving the shape to blank is more significant than applied load capacity. Fig. 14 shows the load-stroke curves for dome shape forming.

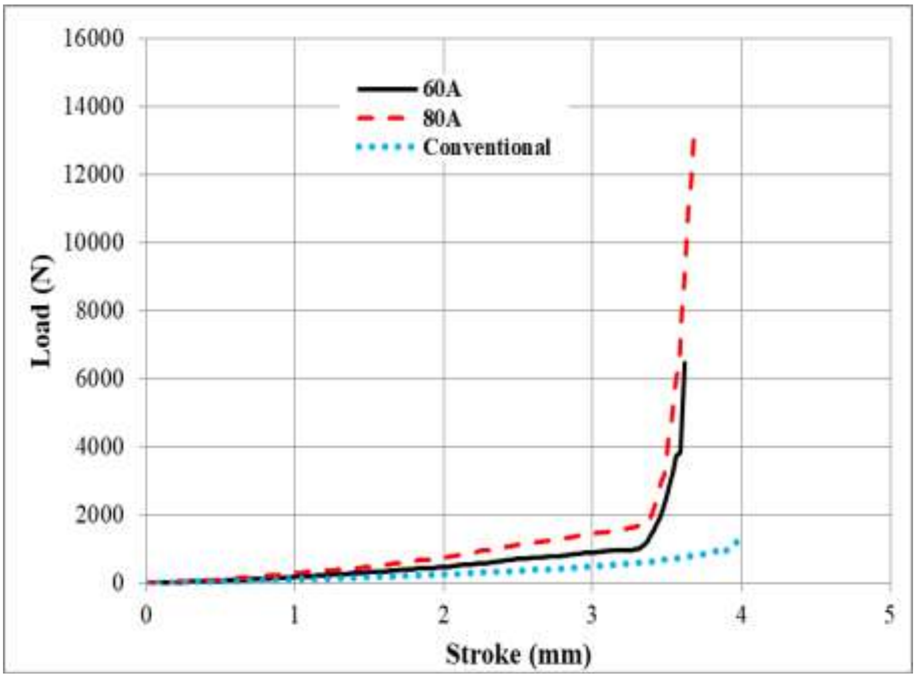

Fig. 14 Load-Stroke Curves for Dome Shape

B. Experimental Results

As a mentioned in above, experiments were conducted on dome shape by using 60A polyurethane rubber. Aspect of dome shape after experimental study is shown in Fig. 15.

Fig. 15 Specimens after Experiments

For verification the FE results and experimental results, load – strokes load-strokes curves of dome shape between 60A numerical and 60A experimental results were used. Graph in Fig. 16 shows the load-stroke curves.

In dome shape forming, experimental maximum stroke was acquired as 3.66 mm for complete forming but in numerical result maximum stroke was 3.62 mm. This difference may be caused by changes in measuring instruments or in the environmental conditions, is called as random errors in experiment. Maximum loads in experiment and numerical analysis have been obtained as 7290 N and 6476 N respectively. Then, difference between experimental study and numerical analysis in maximum load was obtained as 5.46 %. This is the applicable difference to verify the numerical results. Also, nearly between 2.5 mm and 3.5 mm stroke loads is higher in experimental results compared to finite element analysis. This situation can be caused by leakage of lubricant. After some travel of punch, lubricant material was squeezed and leaked out from small gaps of die set. So, this increases the friction between contact surfaces.

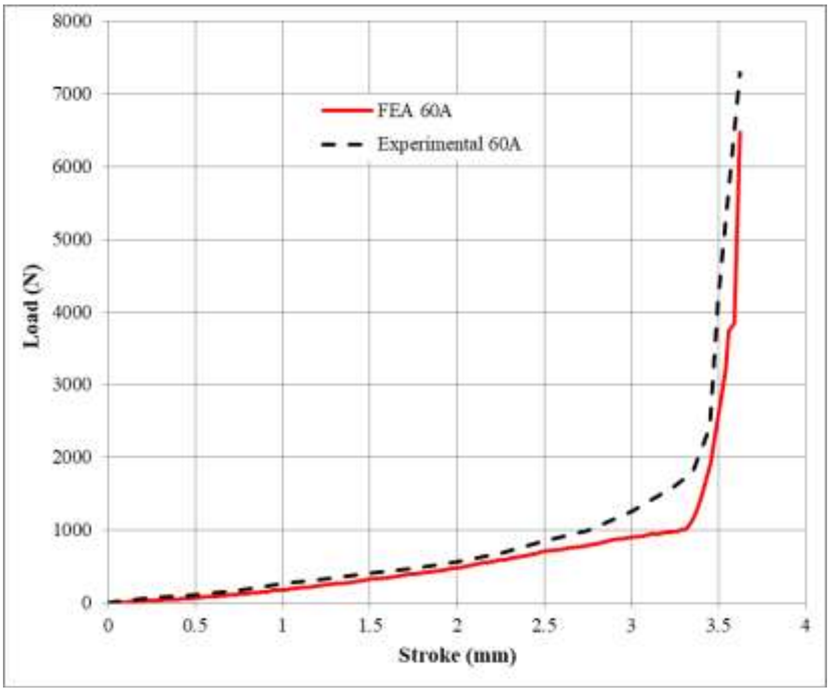

Fig. 16 Load-Stroke Curves of Numerical and Experimental 60A Rubber-Pad Forming for Dome Shape

IV. CONCLUSIONS

In this paper the rubber-pad forming experiments and simulations were performed to form aluminum blanks with two types of rubber materials. Finite element simulations were carried out using commercial software DEFORM™ 2D to analyze the process. The FE loads are compared with experimental measurements to validate the FE model. The main conclusions of this research are summarized below:

- Hardness of polyurethane material directly affects the formability of blank. Harder polyurethane is appropriate to form the desired shape on sheet. However, more loads are required compared to softer polyurethane and conventional forming type.
- Flexible die forming is very applicable for forming of small sizes of mesoscale or miniaturized parts without excessive thinning.
- Rubber pad forming is suitable process financially and time consuming. Because, it uses the half of die as a rigid. Also, producing of die with small dimension is expensive and needed to skilful operators for mesoscale or miniaturized parts. And, the arrangement of die set takes very short time compared to conventional forming.

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