

Analytical and Experimental Analysis of Axisymmetric Deep Drawing Process

N. Arab

Department of Material Science
Islamic Azad University, Saveh Branch, Saveh, Iran
E-mail: najarab@yahoo.com

Received: 23 August 2013, Revised: 4 October 2013, Accepted: 8 December 2013

Abstract: There are mainly two methods of deep drawing analysis; experimental and analytical/numerical. Experimental analysis can be useful in analyzing the process to determine the process parameters in producing a defect free product. The analytical/numerical modeling can be used to model and analyze the process through all stages of deformation. This approach is less time consuming and more economical. Sheet metal forming often includes biaxial in-plane deformation with non-proportional strain paths. In deep drawing of cylindrical cup, the deformation in the flange is dominated by pure shear deformation, while it changes to plane strain when the material is drawn into the die. This paper deals with the analysis of deep drawing of circular blanks into axi-symmetric cylindrical cup using numerical modeling. The blank drawability has been related both theoretically and experimentally with the initial diameter of the blank and deep drawing parameters. The strains in the radial and circumferential directions have been measured. A correlation on the flange thickness variation by taking into account the work hardening with the analytical and experimental values also has been searched.

Keywords: Analytical Analysis, Axisymmetric Sheet Metal Forming, Experimental Analysis, Deep Drawing

Reference: Arab, N., "Analytical and Experimental Analysis of Axisymmetric Deep Drawing Process", *Int J of Advanced Design and Manufacturing Technology*, Vol. 7/ No. 2, 2014, pp. 59-66.

Biographical notes: N. Arab received his PhD in Mechanical Engineering from National Academy of Science, Armenia, in 2010. He is currently Lecturer at the Department of Material Science, Islamic Azad University, Saveh Branch, in Iran. His current research interest includes Sheet Metal Forming and Dislocation Theory.

1 INTRODUCTION

Production of high quality products in a short time and at low cost is an ultimate goal in manufacturing. To reach this goal, continuous progress made at the design and at the shop floor levels of forming process [1]. The stages of research and development in CAD/CAM/CAE in relation with the analysis and design of forming parts can be observed from several papers published in proceedings of international meetings [2-3]. To avoid trial and error tryout procedures, the sheet metal forming simulation is increasingly being used in the stamping industry to evaluate the deformation paths and the forming defects such as fracture and wrinkling. Many research groups are still developing and improving finite element codes for the analysis when an initial design of the blank and the tools is done and when the forming conditions are defined.

Several tool analyses are described in the proceedings [2-3]. They are based on membrane, shell or even solid elements, considering static or dynamic, implicit or explicit approaches. These tool analyses could be very precise if used by well-trained engineers, but they are time consuming and needs expensive computer resources. Computer simulation can also be very attractive and helpful for the process and tooling engineers to define the initial blank (thickness, contour and surface), some process parameters (boundary conditions, holding forces, lubrication conditions, drawbead types and positions, etc.) and the material properties (yield stress, hardening, anisotropy, etc.).

This has been recognized by some industrial and academic research and development groups. As a result, a number of methods have been developed in the last decade. They are mainly based on the fact that the shape of the desired part is known. A comparison is then made with the initial flat blank to estimate the deformation of the final product taking into account simple constitutive equations and assumptions regarding the tool actions. These simplified procedures have been called different names: ‘geometrical mapping method’ [4], ‘single and multi-stage forming formulations’ [5], ‘one step solution’ [6], ‘ideal forming theory’ [7], ‘Inverse Approach’ (IA) [8-12] and ‘Simplified Approach’ [13].

The inverse approach is based on a discretization of the final workpiece by simple triangular flat facet shell elements. For a large number of industrial applications, the membrane effects are dominant, but it has been necessary to consider bending effects using a simple discrete Kirchhoff shell element [14-16]. Assumptions were made regarding the action of the tools (punch and die) at the end of the forming process. Logarithmic strains and total deformation theory of plasticity were considered. The equilibrium of the workpiece leads to a

set of nonlinear equations. These nonlinear equations could be solved by different techniques such as the Newton–Raphson static implicit approach, the dynamic relaxation method or the dynamic explicit algorithm [17-21].

The convergence difficulties can be encountered for practical situations involving deep drawing workpieces (with almost vertical walls) and a low plastic hardening law. A simplified scheme in order to estimate the trimming part of the workpiece for a given blank shape, flat or curved has been developed. The inverse approach has been continuously evaluated by comparing the numerical results with experimental and other numerical results obtained by incremental approaches. The procedure has been found very efficient and quite precise at the preliminary tool design stage [22-23]. Based on the idea of the simplified inverse approach two industrial codes have been developed [24-26]. The codes are routinely used at the preliminary forming design stage of car panels and thin walled structural members. Some backwards simulation codes have been developed and used in the industry [27-29].

In this paper, in order to increase the efficiency and accuracy of the modeling procedure, the yielding criteria and radial and circumference strains among with strain hardening and thickness variations during the forming process has been employed. Moreover experimental results are present to evaluate the theoretical method.

2 THE DIFFERENT DEFORMATION MODES

Figure 1 shows different deformation modes that can occur in a cup drawing.

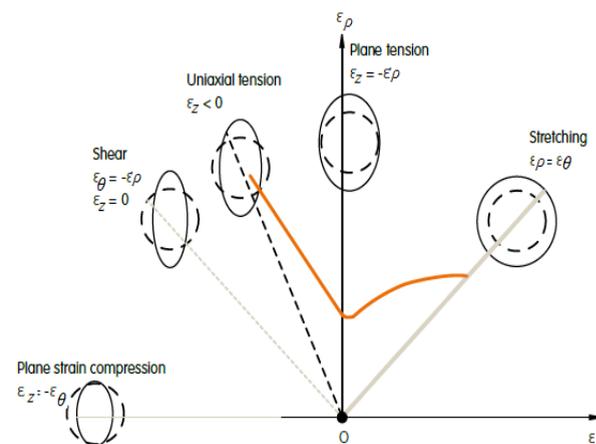


Fig. 1 Strain diagram for steel forming showing a typical forming limit curve for steel blanks [30]

By convention, any type of deformation in a sheet can be represented by a point in the ϵ_ρ vs ϵ_θ diagram, where ϵ_ρ is the principal strain in the plane of the sheet and ϵ_θ is the strain perpendicular to ϵ_ρ . The thickness strain ϵ_z is obtained from the conservation law of volume: $\epsilon_\rho + \epsilon_\theta + \epsilon_z = 0$.

This diagram illustrates different possible types of deformation during drawing. The deformation mode is visually represented in the chart by the deformation of the circle. In reality, the magnitude and mode of deformation of a component are measured by optical measurement of a full pattern of circles or dots printed on a blank before deformation. Characteristic cases or deformation modes are:

- Biaxial tension: this is accompanied by thinning and typically occurs in spherical shapes such as at the punch nose. The magnitude of deformation is largely defined by the shape and the restraining force on the flange, exerted by the blankholder.
- Plane strain tension: generally occurs in the vertical walls of the part, due to the tensile stress caused by retention under the blankholder, or just before the end of forming when sliding in the tool is restricted.
- Uniaxial tension: this is the situation encountered in a tensile test on a specimen, and it occurs in transition regions between zones of plane strain tension and plane strain compression.
- Shear deformation: represents the ideal forming mode; here, all tensile strains are being compensated by compressive strains, so that the thickness remains constant. This type of deformation can occur beneath the blankholder if the flow is uniform (axisymmetric drawing).
- Drawing: involves thickening due to a reduction in width (circumference). It is mostly unavoidable during deep drawing but can be controlled beneath the blankholder. However, its occurrence in unsupported areas will lead to wrinkling or folding [30].

Sheet metal forming at axisymmetric conditions

The basic analytical theory used in the solution of the problem of deep-drawing of a cylindrical cup is based mainly on the research works in references [31-40]. The analytical model is established on the following assumptions:

- Elastic strains are neglected, since they are small in comparison between plastic strains, and isotropic material.
- Von Misses material with non-linear strain-hardening is used.
- Radial, circumference and thickness directions are considered principal directions.

- Bending/unbending effects are neglected since their effect is negligible for a die profile radius to sheet thickness.
- Shear stress is neglected across the sheet thickness.
- A straight cup wall is assumed.

The principal directions in the problem of deep-drawing of a cylindrical cup are the radial, circumferential and thickness directions with ρ , θ and z designations, respectively. The governing plasticity equations of the analytical model are as follows: effective stress, for a material free from Bauschinger effects, Von Misses or effective stress can be defined as follows [41-42]:

$$\sigma_s = \left\{ \frac{1}{2} [(\sigma_\rho - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_\rho)^2] \right\}^{1/2} \quad (1)$$

Plastic Strains for the three principal directions; circumferential, thickness, and radial directions can be expressed as:

$$\epsilon_\theta = \ln \rho/R \quad \epsilon_z = \ln S/S_0 \quad \epsilon_\rho = -(\epsilon_\theta + \epsilon_z) \quad (2)$$

S_0 is primary thickness of blank and R is primary blank diameter. Effective Strain: The effective incremental strain can be stated as:

$$d\epsilon_i = \left\{ \frac{2}{9} [d\epsilon_\rho - d\epsilon_\theta]^2 + (d\epsilon_\theta - d\epsilon_z)^2 + (d\epsilon_z - d\epsilon_\rho)^2 \right\}^{1/2} \quad (3)$$

Stress-Strain Relationship: Based on Levy-Lode stress-strain relationship:

$$d\epsilon_\rho = \frac{3}{2} \frac{d\epsilon_i}{\sigma_s} (\sigma_\rho - \sigma_0), \quad (4)$$

$$d\epsilon_\theta = \frac{3}{2} \frac{d\epsilon_i}{\sigma_s} (\sigma_\theta - \sigma_0), \quad (5)$$

$$d\epsilon_z = \frac{3}{2} \frac{d\epsilon_i}{\sigma_s} (\sigma_z - \sigma_0), \quad (6)$$

Flow Equation: The flow equation that describes the strain hardening of the material is the Ludwik-Hollomon power law which is given by [41-42]:

$$\sigma_s = K \epsilon^n \quad (7)$$

After the drawing process, the drawn parts were cut in rolling direction and the thickness was measured according to Fig. 3.

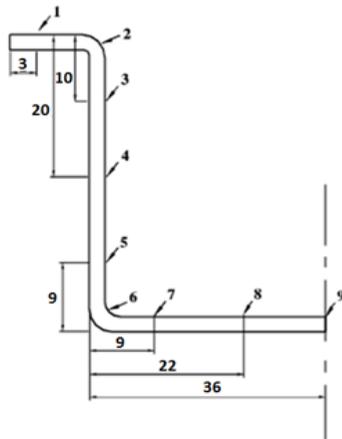


Fig. 3 Measuring positions in drawing cups

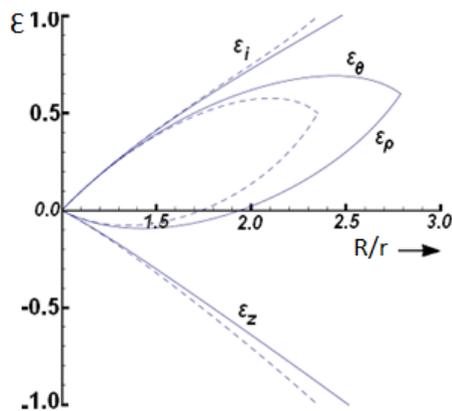


Fig. 4 Distribution of non-dimensional equivalent and major strains for ring plates (r is punch diameter)

3 RESULTS AND DISSCISSION

Analytical Modeling

Taking into account Eqs. (3) and (13) and using computer MATLAB software to draw these equations, the relationship between the major strains in radial, circumference and thickness directions and equivalent strain can be obtained while the effect of work hardening has been considered as shown in Fig. 4. Using Fig. 4, the major strains in radial, circumference and thickness directions and equivalent strain can be measured after deep drawing process.

Experimental Results

The thickness measuring results from 9 positions in 24 drawn parts are presented in table 3. Also, Fig. 5 shows

maximum thinning and thickness positions in drawn cups. According to the results of this research, for a blank with 2 mm thickness, the maximum thinning in drawn cups, occur in position 6 and it is next to 18% of blank thickness. Also the maximum thickness takes in position 1 and it is next to 1.11% of initial blank thickness. The schematic thickness changes in drawn cup during deep drawing process are shown in Fig. 6.

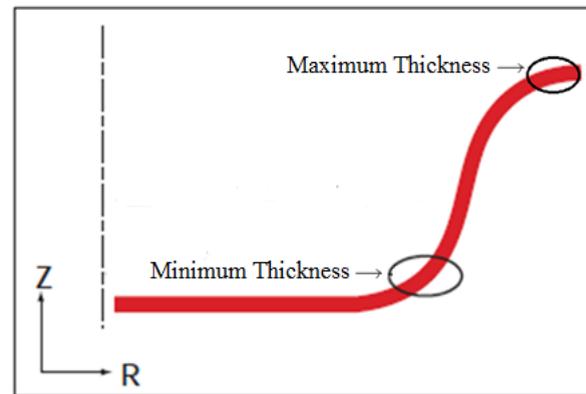


Fig. 5 Maximum and minimum thickness positions in drawn cup

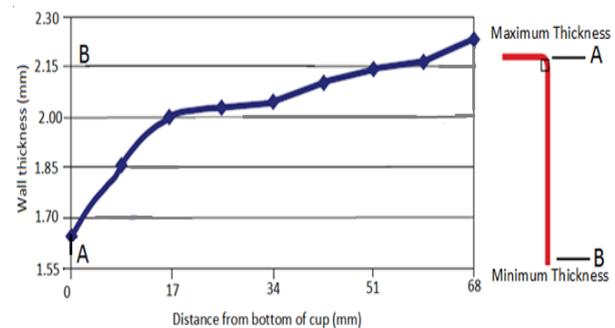


Fig. 6 Schematic illustration of thickness changes in cup drawing Process according to table 3 and Fig. 3

4 CONCLUSION

An analytical model to calculate the radial, circumference, thickness and equivalent strains of drawn cup has been developed by taking in to account work hardening effect. Experiments were conducted to evaluate theoretical analysis, where the experimental results are in agreement with theoretical results. The analysis method is useful for the prediction of thickness variation of the products prior to the carrying out of the actual drawing process. The analysis may be used to estimate the critical thickness that initiates the failure of the products and also to set the minimum clearness between the die and punch for the consequent ironing process.

Table 3 The thickness measurement results of experiments related to Fig. 3

Experiment	1	2	3	4	5	6	7	8	9
Position									
1	2.22	2.21	2.12	1.87	1.76	1.70	1.76	1.76	1.76
2	2.22	2.13	2.11	1.85	1.75	1.70	1.76	1.76	1.76
3	2.21	1.97	2.13	1.74	1.73	1.68	1.76	1.74	1.76
4	2.15	2.13	2.02	1.74	1.74	1.68	1.76	1.76	1.74
5	2.13	2.11	2.02	1.72	1.74	1.69	1.76	1.76	1.74
6	2.18	2.11	1.84	1.72	1.76	1.68	1.76	1.76	1.75
7	2.18	2.12	1.84	1.85	1.85	1.70	1.84	1.84	1.84
8	2.09	2.07	2.02	1.72	1.74	1.66	1.74	1.74	1.74
9	2.06	2.07	1.95	1.66	1.69	1.64	1.74	1.74	1.74
10	2.09	2.07	2.06	1.78	1.69	1.69	1.64	1.72	1.72
11	2.18	2.11	1.99	1.72	1.76	1.72	1.74	1.74	1.74
12	2.15	2.11	2.02	1.74	1.72	1.70	1.72	1.74	1.74
13	2.13	2.11	2.00	1.70	1.73	1.72	1.74	1.74	1.74
14	2.19	2.14	2.05	1.74	1.75	1.72	1.75	1.74	1.74
15	2.19	1.89	2.04	1.73	1.74	1.67	1.74	1.74	1.74
16	2.16	2.14	2.01	1.75	1.78	1.71	1.75	1.78	1.75
17	2.21	2.14	2.14	1.83	1.78	1.81	1.72	1.78	1.78
18	2.20	2.12	2.02	1.77	1.77	1.73	1.78	1.77	1.77
19	2.20	2.15	2.06	1.80	1.75	1.72	1.77	1.77	1.77
20	2.20	2.15	2.15	1.86	1.79	1.75	1.72	1.77	1.77
21	2.12	2.08	2.02	1.74	1.74	1.68	1.77	1.77	1.74
22	2.15	2.07	1.99	1.71	1.69	1.68	1.74	1.75	1.75
23	2.12	2.09	1.99	1.74	1.71	1.68	1.74	1.76	1.76
24	2.16	2.12	2.03	1.85	1.85	1.71	1.76	1.78	1.75
25	2.19	2.16	2.06	1.78	1.79	1.72	1.77	1.76	1.76

REFERENCES

- [1] Sattari, H., Sedaghati, R., and Ganesan, R., "Analysis and design optimization of deep drawing process, Part 1. Three dimensional finite element and sensitivity analysis", *J. Mater. Process. Technol.*, Vol. 184, 2007, pp. 84-92.
- [2] Kroplin, B., Luckey E., "Metal forming process simulation in industry", International Conference and Workshop, Baden-Baden, Germany, 1994, pp. 28-30.
- [3] Lee, J. K., Kinzel, G. L.; and Wagoner, R. "Numerical simulation of 3D sheet metal forming processes, verification of simulations with experiments", Third International Conference on NUMISHEET 96, the Ohio State University, September 1994, Dearborn, MI. USA.
- [4] Gerdeen, J. C., Chen, P. "Geometric mapping method of computer modeling of sheet metal forming", NUMISHEET 89, 1989, pp. 437-444.
- [5] Chung, K., Lee, D., "Computer-aided analysis of sheet material forming processes", First International Conference on Technology of Plasticity, Vol. 1, Tokyo, Japan, 1984, pp. 660-665.
- [6] Sklad, M. P., Yungblud, B. A., "Analysis of multioperation sheet forming processes", NUMISHEET 92 1992, pp. 543-547.
- [7] Chung, K., Richmond, O., "Sheet forming process design on ideal forming theory", NUMISHEET 92 1992, pp. 455- 460.
- [8] Batoz, J. L., Duroux, P., Guo, Y. Q., and Detraux, J. M., "An efficient algorithm to estimate the large

- strains in deep drawing”, NUMISHEET 89, 1989, pp. 383-388.
- [9] Batoz, J. L., Naceur, H., Barlet, O., Guo, Y.Q., and Knopf-Lenoir, C., “Optimum design of blank contours in axi-symmetrical deep drawing process, in: Z. Wan-Xie, C. Geng-dong, Xi-Kui Li (Eds.)”, *Advances in Computational Mechanics*, International Academic Publisher, 1996, Beijing, China, pp. 113-125.
- [10] Guo, Y. Q., Batoz, J. L., Naceur, H., Bouabdallah, S., Mercier, F., and Barlet, O., “Recent developments on the analysis and optimum design of sheet metal forming parts using a simplified inverse approach”, *Comput. Struct.* Vol. 78, 2000, pp. 133-148.
- [11] Naceur, H., Delam’eziere, A., Batoz, J. L., Guo, Y. Q., and Knopf-Lenoir, C., “Some improvements on the optimum process design in deep drawing using the inverse approach”, *J. Mater. Process. Technol.*, Vol. 146, No. 2, 2004, pp. 250-262.
- [12] Barlet, O., Batoz, J. L., Guo, Y.Q., Mercier, F., Naceur, H., and Knopf-Lenoir, C., “The inverse approach and mathematical programming techniques for optimum design of sheet forming parts”, *ESDA 96’*, 3rd. Biennial European Joint Conference on Engineering Systems Design and Analysis, Montpellier, France, Vol. 3, July 1-4, 1996, pp. 227-232.
- [13] Chateau, X., “A simplified approach for sheet forming processes design”, *Int. J. Mech. Sci.* Vol. 36, No. 6, 1994, pp. 579-597.
- [14] Dhatt, G., Touzot, G., Maloine S. A., “Unrepr’ésentation de la m’ethode des ’el’ements finisL’Universit’e Laval Qu’ebec”, 1981, Paris.
- [15] Batoz, J. L., Dhatt, G., “Mod’elisation des structures par ’el’ements finis”, Vol. 3, Coques, Ed. Herm’es, 1992, Paris.
- [16] O’neate, E., Kleiber, M., and Agelet de Saracibar C., “Plastic and viscoplastic flow of void-containing metals. Applications to axisymmetric sheet forming problems”, *Int. J. Numer. Methods Eng.*, Vol. 25, 1988, pp. 227-251.
- [17] Matthies, H., Strang, G., “The solution of nonlinear finite element equations”, *Int. J. Numer. Methods Eng.*, Vol. 14, 1979, pp. 1613-1626.
- [18] Owen, D. R. J., Hinton, E., “Finite elements in Plasticity: Theory and Practice”, Pineridge press, 1980, UK, Swansea Uni.
- [19] Peric D., Owen, D. R. J., and Honnor, M. E., “Simulation of thin sheet metal forming processes employing a thin shell element”, FE simulation of 3-D sheet metal forming processes in automotive industry, VDI Verlag, Switzerland, Zurich, 1991, pp. 569-600.
- [20] Hibbitt, H. D., Marcal, P. V., Rice, J. R., “A finite element formulation for problems of large strain and large displacement”, *Int. J. Solids Struct.* Vol. 6, 1970, pp. 1069-1086.
- [21] McMeeking, R. M., Rice, J. R., “Finite-element formulations for problems of large elastic-plastic deformation”, *Int. J. Solids Struct.*, Vol. 11, 1975, pp. 601-616.
- [22] Washizu, K., “Variational Methods in Elasticity and Plasticity”, 1982, Pergamon press, third ed. Oxford.
- [23] Lee, E. H., “Elastic-plastic deformation at finite strains”, *J. Appl. Mech.*, Vol. 36, 1969, pp. 1-6.
- [24] Chung, T. J., “Continuum Mechanics”, Prentice Hall, 1988, USA, New Jersey.
- [25] Arora, J. S., “Introduction to Optimum Design”, Mc Graw-Hill, USA, 1989.
- [26] Vanderplaats G. N., “Numerical Optimization Techniques for Engineering Design With Applications”, McGraw-Hill Inc. USA, 1984.
- [27] Topping, B. H. V., Robinson, D. J., “Selecting non-linear optimization techniques for structural design”, *Intl. J. Comput. Aided Eng. Software Eng. Comput.*, Vol. 1, No. 3, 1984, pp. 48-54.
- [28] Prasad, B., Haftka, R. T., “Optimal structural design with plate finite elements”, *ASCE, J. Struct. Div.* 1979, pp. 105-115.
- [29] Rohan, E., Whiteman, J. R., “Shape optimization of elastoplastic structures and continua”, *Comput. Methods Appl. Mech. Eng.*, Vol. 23, 2000, pp. 68-76.
- [30] Steel Solution, Deep Drawing, www.arcelormittal.com/ Sep. 2010.
- [31] Semenov, E. I., “Handbook of Sheet Metal Forming”, Machinery-Building, Moscow, Russia, 1983.
- [32] Romanovski, V. P., “Handbook of Cold Stamping”, Moscow, Machinery-Building, 1979.
- [33] Kenum, Y. T., Wang, C. T., Saran, M. J., and Wagner, R. H., “Practical Die Design Via Section Analysis”, *Journal of Material Processing Technology*, 1992, Vol. 35, pp. 1-36.
- [34] Popov, E. A., “Foundations of Sheet Metal Forming Theory”, Machinery-Building, Moscow, Russia, 1977.
- [35] Popov, E. A., Kovalyov, V. G., “Technology of Sheet Metal Forming”, Bauman MSTU Publication, Moscow, Russia, 2003.
- [36] Storoshev, M. V., Popov, E. A., “Theory of Metal Forming Proceeding”, Machinery-Building, Moscow, Russia, 1977.
- [37] Hosford, W. F., *The Mechanics of Crystals and Polycrystals*, Oxford University Press, USA, 1993.
- [38] Chung, S. Y., Swift, H. W., “Cup drawing from a flat blank, part II, analytical investigation”, *Proceeding of the Institution of Mechanical Engineers*, London, UK, Vol. 165, 1951, pp. 211-228.
- [39] Woo, D. M., “On the complete solution of a deep-drawing problem”, *International Journal of Mechanical Science*, Vol. 10, 1968, pp. 83-94.
- [40] Mahdavian, S.M., He, D., “Product thickness analysis in pure cup drawing”, *Journal of Material Processing Technology*, Vol. 51, 1995, pp. 387-406.
- [41] Marciniak, Z., Duncan, J. L., and Hu, S. J., “Mechanics of Sheet Metal Forming”, Butterworth-Heinemann, Oxford, USA, 2002.
- [42] Hosford, W. F., Caddel, R. M., “Metal Forming, Mechanic and Metallurgy”, 3 rd ed. Cambridge Uni. Press. MI, USA, 2007.
- [43] Nazaryan, E., Konstantinov, V., “Kinematics of Straining in Deformation Operations of Sheet Stamping”, *Bulletin of Machine-building*, Vol. 2, 1999, pp. 35-41.

- [44] Arab, N., Nazaryan, E., "Modeling deep drawing of cylindrical cup", International Journal of Applied Engineering Research, Vol. 4, 2009, pp. 2487-2496.
- [45] Arab, N., "New theoretical calculation of limit drawing ratio by taking into account material parameters changes during deep drawing of cylindrical cup", International Journal of Theoretical and Applied Mechanics, Vol. 5, 2010, pp. 139-146.
- [46] Arab, N., Nazaryan, E., Arakelyan, M., and Markosyan, A., "Mechanics of forming thin ring plates", IDDRG International Conf. 1-3 June 2009, Golden, Co., USA.
- [47] Arab, N., Nazaryan, E., "Stress and strain paths in deep drawing of cylindrical cup", International Research Journal of Engineering Science, Technology and Innovation (IRJESTI), Vol. 2, No. 3, 2013, pp. 51-56.