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INVESTIGATING ALUMINUM SHEET WRINKLING DURING THE DEEP DRAWING PROCESS

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Summary

The purpose of this study is to consider the effect of different parameters on the wrinkling phenomenon of square cups during the deep drawing process. An experimental system was prepared which consisted of a hydraulic press capable of applying different loads on the sheet metal blank and a blank holder and the process was controlled by a computer. All simulations were performed by using the ABAQUS/EXPLICIT V6.9 software, and the effect of different aluminium alloys, punch and die radius, blank holder force, blank holder gap, and friction coefficient on the wrinkling phenomenon has been investigated. Moreover, the minimal blank holder force was obtained by plotting minor strain with respect to the major strain of produced cups, and obtaining the maximum height of wrinkle in a cup. The wrinkling phenomenon was further investigated on different alloys such as A6111-T4, AA5754-O and Al-1050. The results imply that increasing the blank holder force and friction coefficient on the one hand and reducing the blank holder gap, punch radius, and die radius on the other hand, may lead to a reduction in wrinkling during the deep drawing process. Nevertheless, under the same circumstances of the deep drawing process, the wrinkling of the A6111-T4 alloy is more significant compared to the Al-1050 and AA5754-O alloys, while the Al-1050 alloy needs less blank holder force to avoid wrinkling. Using this simulation program it is possible to easily simulate the wrinkling of sheet metal blanks with the least number of trial and error.

Key words: *deep drawing, aluminium, wrinkling, square cups, punch, failure, die radius*

1. Introduction

Deep drawing process is the most important practice in the sheet metal forming which is widely used in industry for transforming sheet metal blanks into hollow parts without seam. This process has a wide application in producing parts with different shape and size. For the process of deep drawing, different factors such as workpiece material, tooling parameters, plastic deformation mechanism, and material flow control must be taken into consideration, [1, 2], as thin-walled cups are extensively employed in the industry. Deep drawing operation, which is known as one of the metal forming processes, is being investigated by many researchers worldwide. The majority of surveys concentrate on the limit drawing ratio (LDR) in plastic deformation, or problems occurring during the deep drawing process, such as folding, wrinkling, and tearing [3].The die parameters affecting the deep drawing process are the die and punch radius, clearance between punch and die, press speed, lubrication conditions, and the type of restraint to metal flow, such as draw bead, blank holder gap (BHG), and blank holder force (BHF) [4, 5]. These parameters have been investigated by many researchers [6, 7, 8], including the current studies [9, 10, 11]. At present, research particularly focuses on the earing reduction in magnesium and aluminum alloys [12, 13]. In this study, 2mm thick aluminum sheets of AA5754-O, Al-1050 and A6111-T4 aluminum alloy materials are used to investigate the effective parameters of wrinkling during the deep drawing process, and to further compare the experimental and numerical results. A blank holder system is developed with computer control in accordance with the BHF control and the optimum BHF for the formability of the material.

In this study, the effects of the sheet material, blank holder force, blank holder gap, friction coefficient, punch radius and die radius on wrinkling phenomena are simulated and the results are compared with practical results. The deep drawing process simulation may lead to savings in time and costs, and an acceptable outcome can be achieved easily. Through the simulation approach, the minimum blank holder force for preventing the wrinkling of aluminum alloys is easily computed. Furthermore, by fixing the blank holder force, the effects of the clearance between the matrix and the blank holder, different punch and matrix radius, and friction coefficient on the wrinkling height of aluminum alloys are investigated.

2. Experimental equipment

2.1 Press and blank

In the forming process, a 60-ton hydraulic press is used, where the cylinder diameter of the blank holder is 60mm and the loading force is computer controlled. The blank used in this process has 61.75 mm in diameter and is 2mm thick. When the forming process is completed, a square cup is produced as shown in Fig. 1.

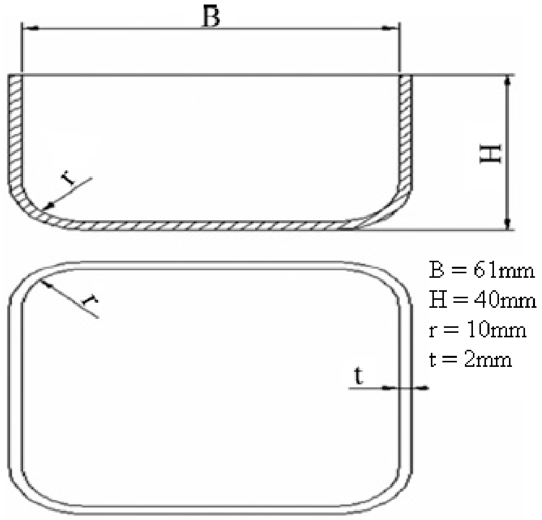


Fig. 1 Square cup dimensions [3]

2.2 Material composition (sheet & blank)

The composition of the AA5754-O aluminium alloy used in this study is presented in Table 1. Al-Mg is not a hardenable alloy and contains 6% Mg and 0.7% of other alloys. Its corrosion resistance to seawater is extraordinary. Mechanical properties of Al-Mg are similar to those of pure aluminium [3], however, when its magnesium content exceeds 6%, Al-Mg processing and welding become more difficult. Al-Mg also suffers from corrosion due to tension, while due to its anodic reaction with oxygen, it is highly resistant to corrosion.

Table 1 Material composition of AA5754-O [3]

Alloy	Mg	Si	Cu	Fe	Mn	Cr	Ti	Al
AA5754-O	2.6-3.6	≤0.4	≤0.4	≤0.4	≤0.4	≤0.4	≤0.4	Balance

3. Experimental test

Square cup drawing processes were carried out with BHFs between 0.5 to 16 MPa. Fig. 2 illustrates cups formed with different BHFs. All deep drawing processes were performed at a fixed force in one step at the drawing speed rate of 2.1 m/min [3].

3.1 Wrinkling and tearing limits

During deep drawing tests the most wrinkling occurred at the BHF of 1.3 MPa or less, while at the BHF of 18 MPa or above, the workpiece would tear off [3]. For accomplishing greater depth, a smother surface, and more uniform thickness during the deep drawing process, different BHFs were determined to achieve the wrinkling and tearing limits [15, 16].

3.2 Influence of different blank holder forces

Due to the fact that the present material is anisotropic, the formation of peculiar earrings around the neck would increase proportionally to an increase in the BHF [17]. The blank holder force is an important factor in preventing sheet wrinkling, in such a way that increasing the BHF may lead to less wrinkling, however, increasing the BHF beyond the limit may cause tearing as shown in Fig. 2. Cup depths produced by the deep drawing process at different blank holder forces are presented in Table 2.

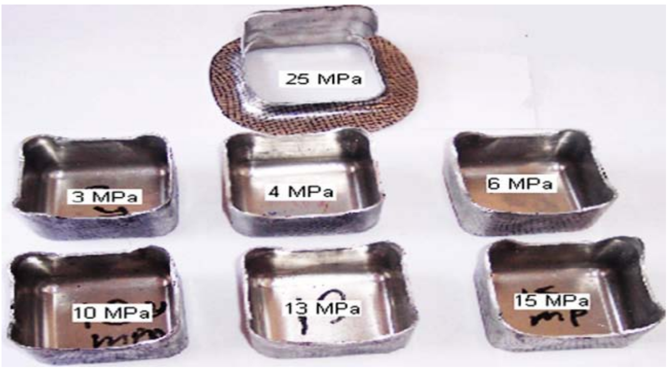


Fig. 2 Square cups formed with different BHFs [3].

Table 2 Square cup depths with various BHFs [3]

BHF	1MPa	4MPa	8MPa	10MPa	16MPa
Square cup depths (mm)	36.7	37.3	38	38.5	39.2

4. Numerical modelling

Abaqus is one of the most capable finite element analysis package used for the computer aided analysis of sheet metal forming processes in the industry. The die, blank holder and sheet metal utilized in this experimental study were created in a 1:1 scale using the Abaqus/CAE of the Abaqus software for the purpose of numerical modelling (Fig.3). The blank holder employed for the simulation had the same dimensions as in the experiment. In the performed simulation, the blank elements used were of the S4R type (S: shell element, 4: the number of nodes, R: reduced integration). The number of elements was 6716, and due to the precise divisions applied to the blank, no error existed on the elements. The numbers of elements were 3051, 5945, and 1683 for punch, matrix, and blank holder, respectively, all of which had square shape elements, type R3D4. The blank model contained 6716 4-node shell quadrilateral elements and was accurately partitioned.

When the simulations were performed and the general model of the process was prepared, various parameters of the sheet material such as blank holder force, blank holder gap (fixed gap between die and blank holder), punch radius, die radius, and friction coefficient were investigated. These parameters were examined in order to observe their impact on the wrinkling phenomenon. The testing procedure was designed in such a way that the parameter in question was changed in the process while all other parameters were kept fixed. In addition, in order to find a correlation between the obtained simulation results and the empirical results, anisotropic properties of sheets were taken into consideration.

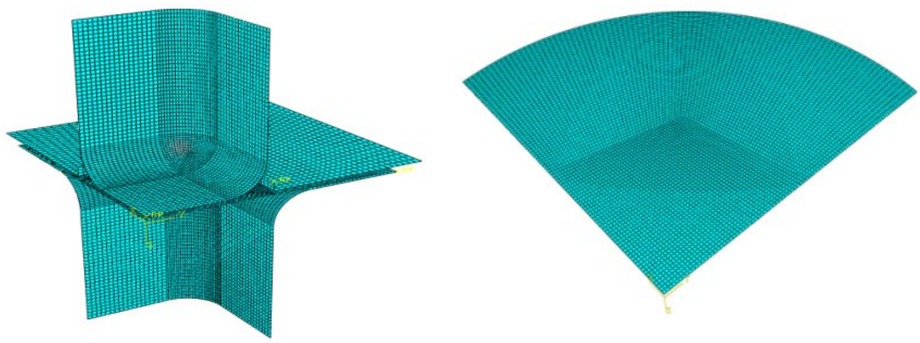


Fig. 3 Numerical model created by Abaqus

4.1 Assigning material properties to sheet

One of the important parameters in Abaqus is to determine the material property. Material properties play a critical role in analyzing the model [18]. Therefore, the die, the blank holder plate, and the punch were identified as rigid materials. The mechanical properties of AA5754-O, Al-1050 and A6111-T4 materials are provided in Table 3.

Table 3 Mechanical properties of AA5754-O, Al-1050 and A6111-T4

Material properties	AA5754-O	AL-1050	A6111-T4*
Specific gravity (kg/m³)	2643	2705	2700
Poisson ratio	0.33	0.33	0.33
Young modulus (GPa)	70.23	69	69
$\sigma = k\varepsilon^n$ Strength coefficient (MPa)	416.5	173.5	----
R 0	0.705	0.67	Normal anisotropy: 0.994
R 45	0.765	0.45	
R 90	0.906	0.73	
Deformation hardening coefficient	0.2939	0.06	----
Yield strength (MPa)	104	121.73	185.92
*Stress-strain curve	454.76- 268.84 exp(- 6.45ϵ)		

5. Numerical results

5.1 Investigation into aluminium sheet wrinkling with different alloys

Figure 4 illustrates studies conducted to determine the effect of wrinkling on three different types of aluminium alloys. According to this diagram, under the same drawing conditions and the blank holder force of 1MPa, the three alloys, i.e. A6111-T4, AA5754-0, and Al-1050, experienced the maximum wrinkling, while the last mentioned suffered the least.

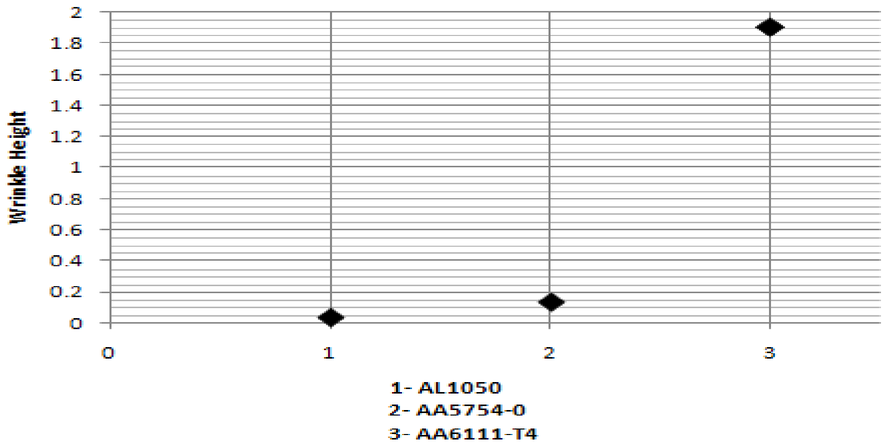
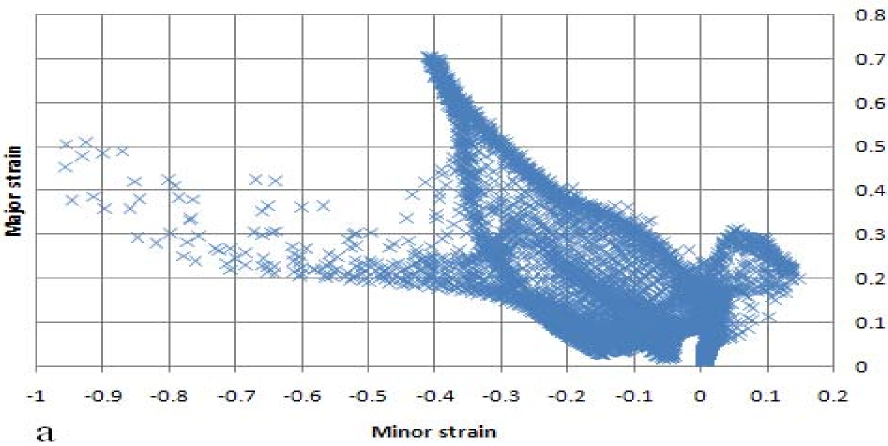


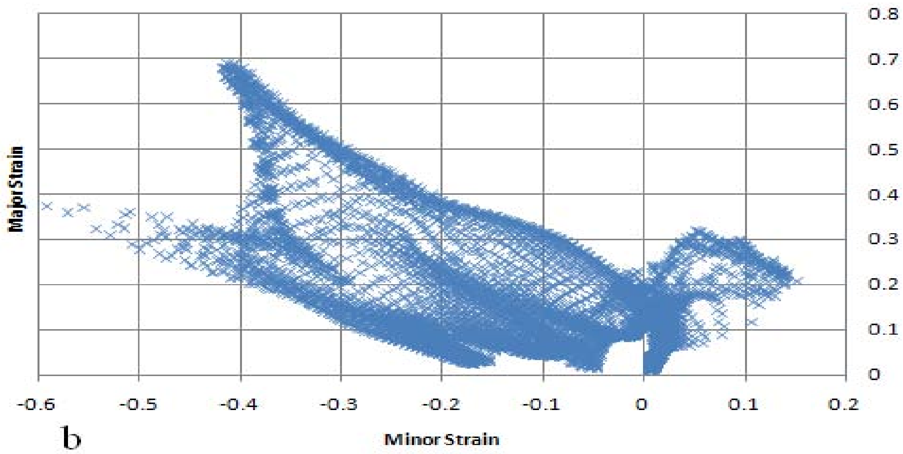
Fig. 4 The effect of wrinkling on different types of aluminium alloys

5.2 Investigating different aluminium sheet wrinkling with different blank holder forces

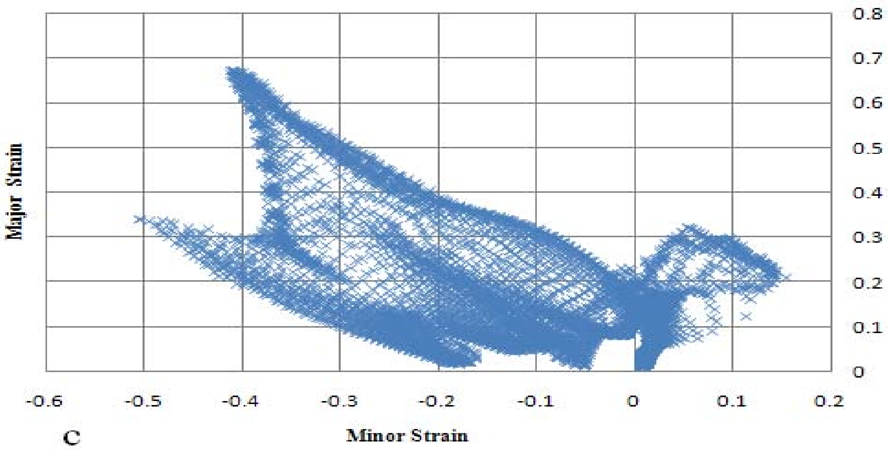
Blank holder force is the most important factor that is applied in order to prevent sheet wrinkling during the deep drawing process. The minimal necessary force for overcoming the wrinkling was obtained by taking this parameter into consideration, with exertion of different blank holder forces under the same condition as in the real situation. Fig. 5 illustrates the strain signatures of AA5754-0 alloys for different blank holder forces, obtained from the Abaqus software. As it is observed, while decreasing the blank holder force, the minimum strain values are lower, and the diagram is shifted to the left; this is due to the increase in wrinkling in the workpiece. However, for blank holder forces of 1.5MPa and above, the shift to the left does not happen, which could be due to the lack of wrinkling.



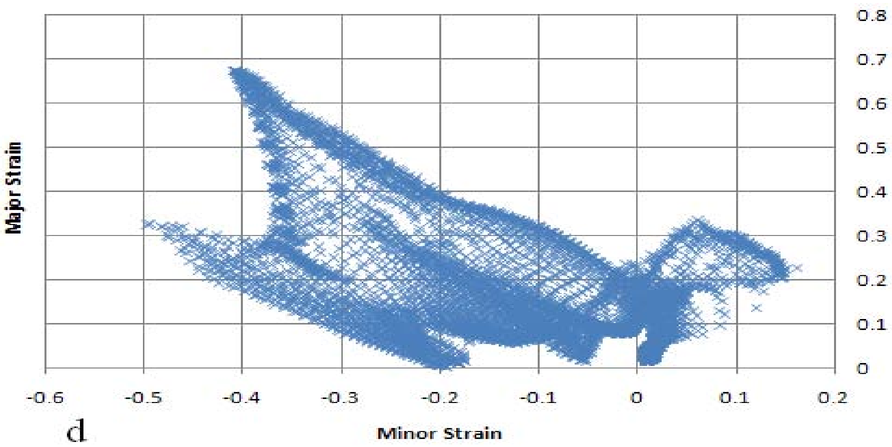
(a) 0.5MPa



(b) 1MPa



(c) 1.5MPa



(d) 2MPa

Fig. 5 Minor strain versus major strain using Abaqus software for different blank holder forces of the square cup (a) 0.5MPa, (b) 1MPa, (c) 1.5MPa, (d) 2MPa

Further investigation and additional measurements of the wrinkle height of the fabricated parts, as can be seen in Fig. 6, showed that wrinkling started on the aluminium sheets (AA5754-0) at the blank holder force of 1.3MPa or less, which is in accordance with the experimental results. Implementing the simulation on the Al-1050 aluminium alloy, the minimal blank holder force for preventing wrinkling, according to Fig. 7, is indicated to be 1.1Mpa, and 2.1Mpa for the AA6111-T4 aluminium alloy, according to Fig. 8.

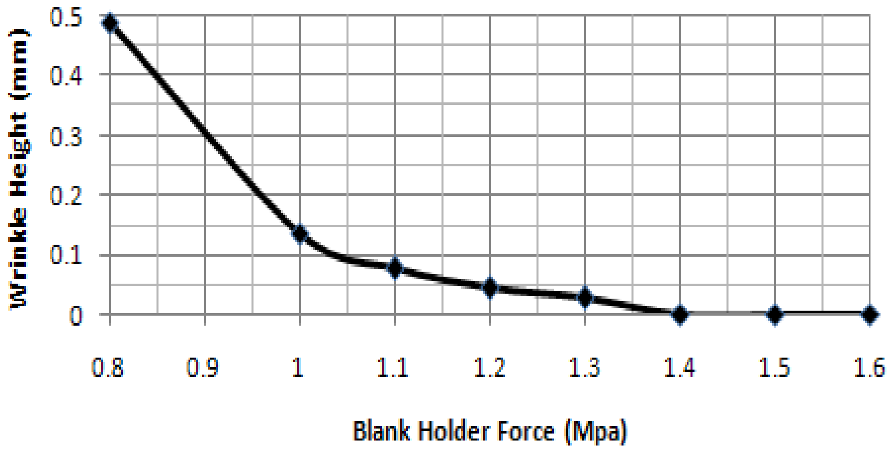


Fig. 6 The effect of different blank holder forces on wrinkling for AA5754-O aluminium alloy

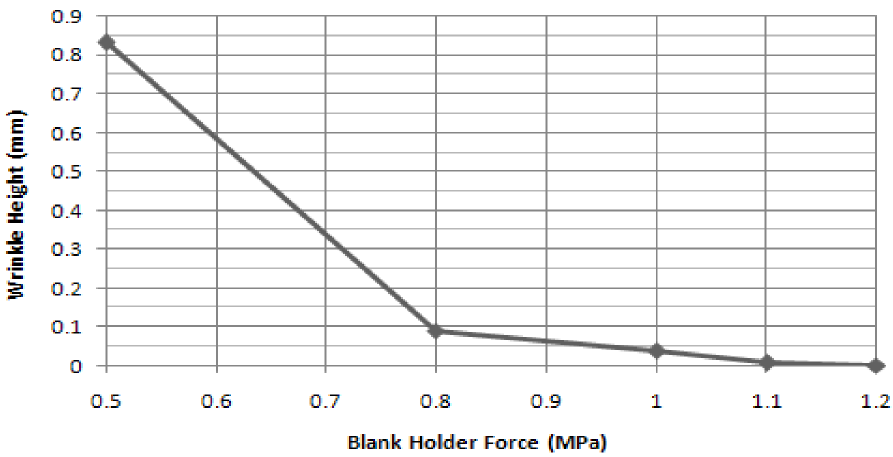


Fig. 7 The effect of different blank holder forces on wrinkling for Al-1050 aluminium alloy

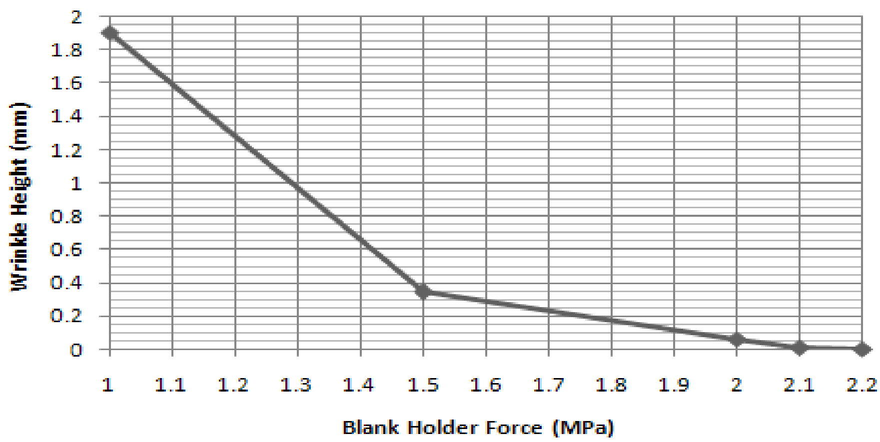


Fig. 8 The effect of different blank holder forces on wrinkling for AA6111-T4 aluminium alloy

5.3 Investigating aluminium sheet wrinkling by varying the gap between die and blank holder

The blank holder gap, defined as the distance between the blank holder and the die surface [19, 20], is an effective parameter for controlling the material flow. The gap between the die and the blank holder should be adjusted in order to restrain wrinkling during process. In empirical studies on quadratic parts and circular blanks of aluminium, if the gap is between 1 to 1.3 times the sheet thickness, no wrinkling may happen. But if this gap exceeds 1.3t, wrinkling starts to develop, and if it goes beyond the limit (1.8t), the sheet is torn because of excessive wrinkling [21]. Fig. 9 shows a change in wrinkle heights in the AA5754-0 aluminium dish when varying the gap between the die and the blank holder. It can be seen that wrinkling starts to appear on the dish at gaps above 2.5mm, which is in accordance with the practical results.

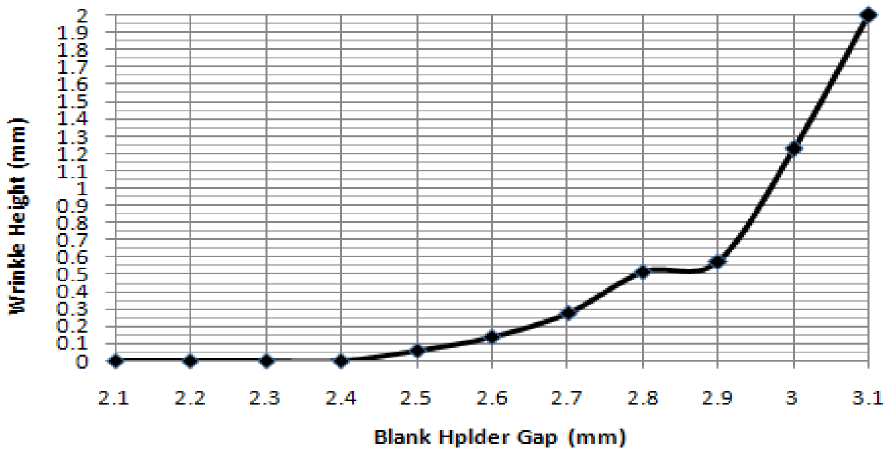


Fig. 9 The effect of varying blank holder gap on wrinkle height

5.4 Investigating aluminium sheet wrinkling by varying punch and die radii

Different radii of the punch and the die proposed in literature and handbooks for achieving a perfect faultless part are between 5 to 10 times the sheet thickness. However, if this value becomes too low, it may cause an increase in the applied force during the process and the sheet may be torn. If the punch radius is excessively large, due to the insufficient surface of contact between the punch and the blank initially, a large portion of the surface remains free under the punch; hence, the metal flow will not be controlled uniformly, which leads to wrinkling in the dish. Similarly, if the die radius is exceptionally large, the substance would be released from underneath the blank holder very quickly, followed by wrinkling in the dish [22]. Figs. 10 and 11 illustrate the wrinkling height of the dish, caused by varying the punch and the die radius, where the sheet material is the AA5754-0 alloy, and the blank holder force is 1MPa. In Fig. 10, the die radius is fixed at 10mm, and in Fig. 11, the punch radius is fixed at10mm.

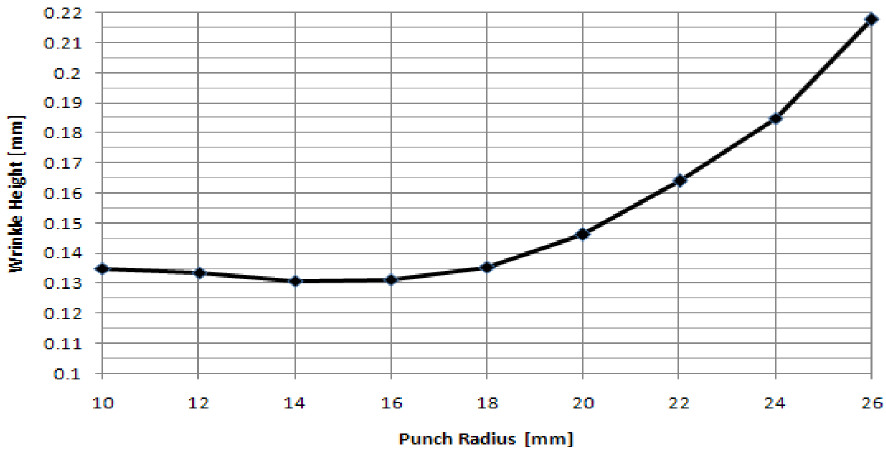


Fig. 10 The effect of varying punch radius on wrinkle height

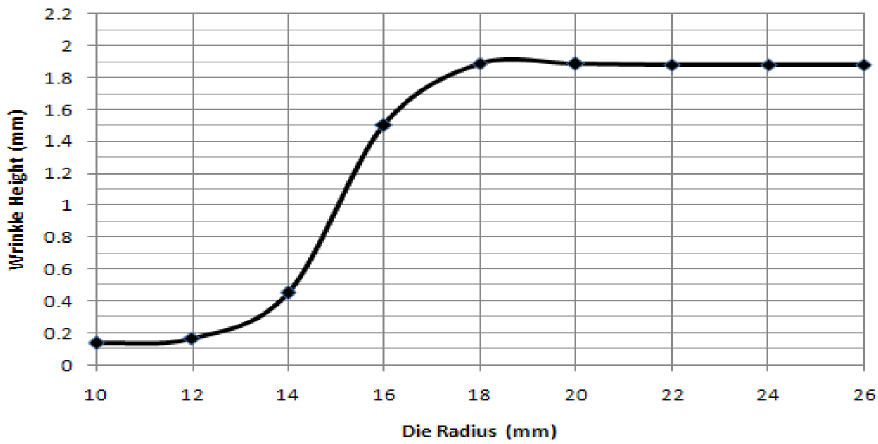


Fig. 11 The effect of varying die radii on wrinkle height

As it is observed, the impact of increasing the die radius on the wrinkling phenomenon is much more significant than in the case of increasing the punch radius. In order to prevent wrinkling, the reasonable range of the punch radius should be 5 to 9 times the blank thickness, and the range for the die radius should be 5 to 7 times the blank thickness. As it is shown in Fig. 11, for radii above 18mm, two wrinkling waves appeared on the workpiece. So, for this reason, the initial wrinkle radius is first reduced slightly and then it starts rising, according to Fig. 12.

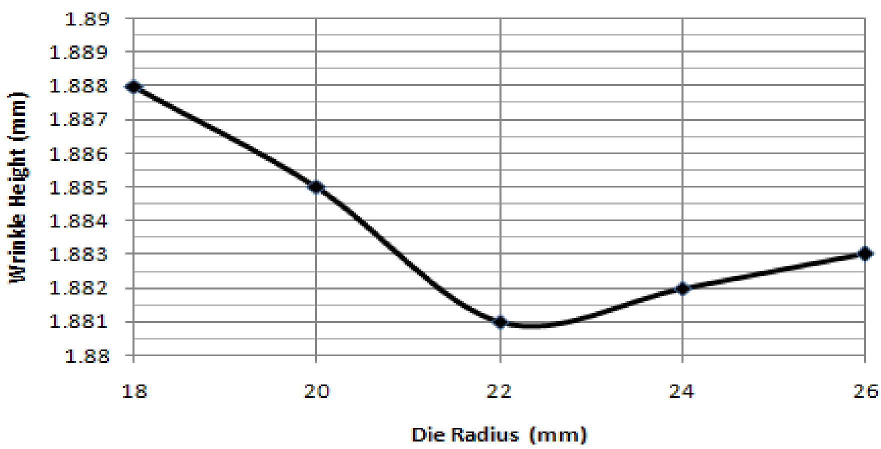


Fig. 12 The effect of varying die radii on wrinkle height for radii above 18mm

5.5 Investigating aluminium sheet wrinkling by varying friction coefficient

One of the important parameters in the deep drawing process is the friction coefficient between the die and the blank surfaces. Any increase in the friction coefficient leads to a reduction in wrinkling of the blank, however, increasing the friction coefficient between the blank surface and the die and the blank holder beyond the limit may cause the sheet to be torn under tension [23]. Fig. 13 illustrates the impact of varying friction coefficients between the blank surface, die, and blank holder. In the related simulation of the AA5754-0 alloy sheet, the friction coefficient between the punch and the sheet is fixed to be 0.12, where the blank holder force is held at 1MPa.

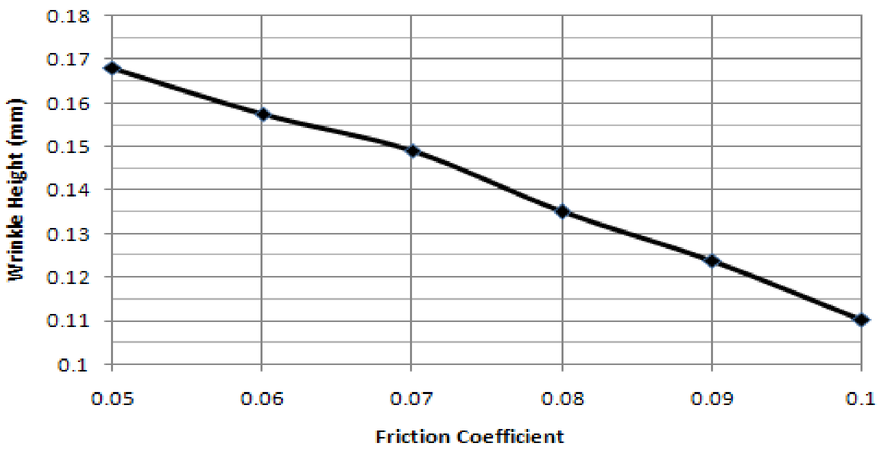


Fig. 13 The effect of varying friction coefficient on wrinkle height

6. Conclusion

In this study, the effects of important parameters of the deep drawing process on the wrinkling of aluminium alloys are simulated and the results are compared with practical results. The simulation approach is easily applicable with the lowest cost by varying the material, the gap between the matrix and the holder, the punch radius, the matrix edge, and the friction coefficient, in order to control wrinkling in aluminium alloys. Wrinkling starts from the outermost area of the sheet and it is usually determined by peculiar shapes of waves throughout the sheet. The number of these waves depends on geometrical features, the sheet material, and other factors such as force, and type of the blank holder. Taking these parameters into consideration, the AA6111-T4 alloy suffered more wrinkling than AA5754-0 and Al-1050 alloys, under the same drawing conditions at 1MPa. Also, the onset of wrinkling in the AA5754-0 aluminium sheet is at the blank holder force of 1.3MPa and below. If we use the fix blank holder rather than the blank holder force, we may expect the dish to wrinkle if the gap between the die and the blank holder is 2.5mm or more. In order to prevent wrinkling, the minimum blank holder force should be 1.1MPa and 2.1MPa for the AA6111-T4 alloy and the Al-1050 alloy, respectively. The increase in the coefficient of friction and the decrease in the punch radius and the matrix radius are very effective in controlling the wrinkling, whereby exceeding these may lead to sheet tearing. All parameters of the deep drawing process are somehow influencing wrinkling, however, it is easy to determine suitable values by simulation. In this study, it is possible to conclude that the FEM analysis approach may lead to desired results regarding the creation of conditions, the blank holder force and the creation of limit diagrams for any sort of material. Therefore, the need for the costly experimental work may be eliminated, leading to time and cost savings during the design and manufacturing phase in industry.

REFERENCES

[1] Y.H. Moon, Y.K. Kang, J.W. Park, S.R. Gong. Tool temperature control to increase the deep draw ability of aluminum 1050 sheet. *Journal of Machine Tools and Manufacture*, 41 (2001) 1283-1294.

[2] M. Janbakhsh, M. Riahi, F. Djavanroodi. A practical approach to analysis of hydromechanical deep drawing of superalloy sheet metals by using finite element method. *Journal of Advanced Design and Manufacturing Technology,* 6 (2013) 1-7.

[3] H.I. Demirci, C. Enser, M. Yasar. Effect of the blank holder force on drawing of aluminum alloy square cup: Theoretical and experimental investigation. *Journal of Materials Processing Technology,* 206 (2008) 152-160.

[4] J. Cao, MC. Boyce. A predictive tool for delaying wrinkling and tearing failures in sheet metal forming. *Journal of Engineering Materials and Technology, Transactions of the ASME*, 116 (1997) 354-365.

[5] SY. Tung, Full film lubrication of deep drawing. *Tribology International*, 32 (1999) 89-96.

[6] A.G. Mamalis, D.E. Manolakos, A.K. Baldoukas. Simulation of sheet metal forming using Eksplisit finite-element techniques: effect of material and forming characteristics. Part 2. Deep-drawing of square cups. *Journal of Materials Processing Technology*, 72 (1997) 110-116.

[7] M.T. Browne, M.T. Hillery. Optimising the variables when deep-drawing C.R.I. Cups. *Journal of Materials Processing Technology,* 136 (2003) 64-71.

[8] F.K. Chen, T.B. Huang, C.K. Chang. Deep drawing of square cups with magnesium alloy AZ31 sheets. *Journal of Machine Tools and Manufacture,* 43 (2003) 1553-1559.

[9] K. Manabe, H. Koyama, S. Yoshihara, T.Yagami. Development of a combination punch speed and blank-holder fuzzy control system for the deep-drawing process. *Journal of Materials Processing Technology,* 125 (2002) 440-445.

[10] M. Karali, Derin Sac C¸ ekme ˙Is¸ leminde Pot C¸ Emberi Baskısının Kontrolu nu n Cidar Kalınlıg U zerindeki Etkilerinin I˙ncelenmesi. *Ph.D. Thesis. Marmara Universitesi Fen Bilimleri Enstitu su, Istanbul*, pp.118, 2005.

[11] M. Gavas, M. Izciler. Deep drawing with Anti-Lock braking system (ABS). *Journal of Mechanism and Machine Theory,* 41 (2006) 1467-1476.

[12] I. Tikhovskiy, D. Raabe, F. Roters. Simulation of earing during deep drawing of an Al-3% Mg alloy (AA5754) using a texture component crystal plasticity FEM. *Journal of Materials Processing Technology*, 183 (2007) 169-175.

[13] T. Walde, H. Riedel. Simulation of earing during deep drawing of magnesium alloy AZ31. *Journal of Acta Materialia,* 55 (2007) 867-874.

[14] Mandić, V. Ć. Predrag. Integrated product and process development in collaborative virtual engineering environment. *Transactions of FAMENA*, 18 (2011) 369-378.

[15] R. Haar, Friction in sheet metal forming, The Influence of (Local) contact condition and deformations. *Ph.D. Thesis. University of Twenty*, Netherlands, 1996.

[16] V. Cvitanić, F.Vlak, Ž. Lozina. An Analysis of non-associated plasticity formulations in deep drawing simulations. *Transactions of FAMENA*, 31 (2007) 11-26.

[17] K. Mattiasson. On Finite element simulation of sheet metal forming process in industry, *European Congress on Computational Methods in Applied Science and Engineering*, Barcelona, (2002), September 11–14).

[18] R. Kergen, P. Jodogne. Computerized control of the blank holder pressure on deep drawing processes. *SAE Technical Papers*, No. 920433, (1992) 51-56.

[19] J. Cao, M.C. Boyce. A predictive tool for delaying wrinkling and tearing failures in sheet metal forming. *Journal of Engineering Materials and Technology, Transactions of the ASME*; 119 (1997) 354-365.

[20] S.Y. Tung, Full film lubrication of deep drawing. *Tribology International,* 32 (1999) 89-96.

[21] M. Gavas, M. Izciler. Effect of blank holder gap on deep drawing of square cups, *Journal of Materials & Design,* 28 (2007) 1641-1646.

[22] I. Suchy. *Handbook of die design*, McGraw-Hill, New York, 2005.

[23] J.T. William. *Handbook of aluminum*, CRC Press, USA, 2003.

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