Numerical and Experimental Study of Parameters Affecting Metal Forming Using Rubber Pads, on Parts with Radius of Curvature

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Abstract: Production and preparation of many parts of the aircraftbody including wings with long length, smooth form, and large radius of curvature are amongst the most important challenges in this industry. In this paper, the effective factors in the rubber padforming method on pieces containing curvature radius, have been investigated by finite element method. The effect of variables such as curvatureradius, sheetthickness, rubber pad thickness, rubber hardness, lubrication condition, spring back phenomena have been analyzed. To validate the finite elementssimulation, the experimental results were compared. Subsequently, other above-mentioned variants were studied. The obtained results indicate that there is a close differentiation between the numerical and experimental works. Moreover, the cited parameters have different effects on part quality as discussed.

Keywords: Finite Element, Radius of Curvature, Rubber Pad Forming, Wings

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1 INTRODUCTION

Production and preparation of parts having radius of curvature has always been accompanied with problems concerning dimension and phenomenon such as spring back. Many small industry companies are recently required to manufacture curved products that are small in lot size, which means higher cost and multiple tools. Today, such parts are made through processes such as stretch forming. However, during production of such parts there are limitations among them partial formation of some parts or not producing blank holders in large scale [1]. To decrease or totally solve these limitations and achieve dimensional precision, different techniques must be used.

A possible alternative forming method, which can reduce production costs for such companies, is flexible forming process (FFP). This process known as rubber pad forming has recently being used in aerospace industry. The rubber forming process uses a rubber pad contained in a rigid box in which one of the tools is replaced by the rubber pad. The rubber pad in this method may be constructed either solid or laminated. The laminated pad is comprised of sheets of rubber placed over one another. The advantage of this is that the working surface can be restored by turning the top layer over or replacing it. The advantages of the rubber pad forming process compared to conventional forming process are[2]:

1. Only a half single rigid tool is required to form a part.
2. Different metals and thicknesses can be formed as no tool marks are created.
3. Set–up time is considerably shorter as no lining–up of tools is necessary.

Several studies have been carried out to analyze rubber-pad forming. Browne and Battikha presented an experimental study of the rubber-pad forming process to investigate the capability of the process and to optimize the process parameters. They analyzed the use of different types of lubricants at the blank and its interfaces [3], [4]. Dirikolu and Akdemirfound that the rubber hardness, blank material type, contact friction and die design are crucial parameters that require adjustment before production [5].

Ramezani et al. presented theoretical models for static and kinetic frictions in rubber–metal and metal–metal contacts. The results of their analysis clearly showed that the new friction models provided better agreement between experiments and results of numerical simulations [6]. Peng et al. investigated the sheet soft-punch stamping process to fabricate micro channels via numerical simulations and experiments [7]. Grain size of the sheet metal, hardness of the soft punch, and lubricant conditions were studied and detailed in their paper.

However, none of these papers studied the influence of different types of rubber and key factors on the parts contain curvature radius. These weaknesses necessitate finding a new approach which considers the influence of different parameters on the process. In this article, experimental and numerical studies using finite element method have been studied on aluminum parts with a curvature radius. The effect of key variables such as curvature radius, sheet metal thickness, rubber pad thickness, rubber hardness, and lubrication conditions are investigated.

2 EXPERIMENTS AND FINITE ELEMENT MODELLING

In this section, equipment for the rubber pad forming is designed to manufacture the aluminum parts with curvature radius. The equipments are composed of four parts: the rigid die with radius of curvature, the aluminum blank, the rubber pad, the steel container enclosing the rubber pad. A schematic of the arrangement used for the experimental procedure is shown in (Fig. 1). Fig. 2 shows the tools including parts made by these tools. The parts have 35 and 50mm radius of curvature. The die and rubber pad retainer are made of steel (ST37). Natural rubber of Shore Hardness 61(SHORE A) and diameter 90 (3×30) are used to stamp the blank.

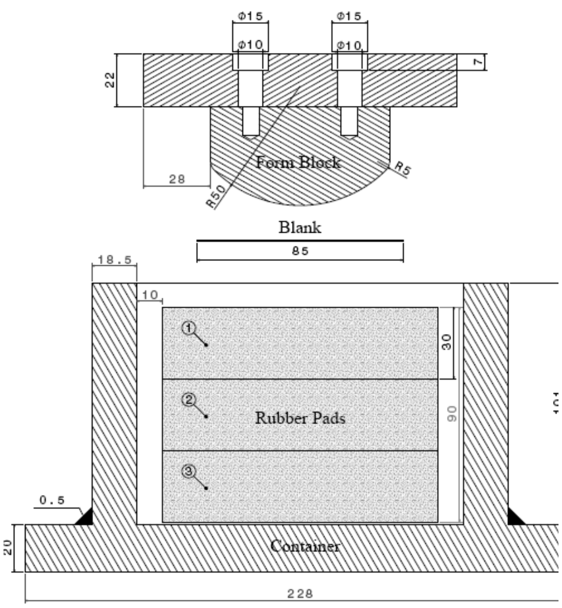


Fig. 1 Schematic representation of rubber pad forming process (mm)

This rubber is used in forming sheets with 90mm length and 0.5 and 1mm thickness. The process begins with the die placed on the hydraulic testing machine. The aluminum blank is then introduced between the form block and the flexible punch.

At this stage, the form block moves down to stamp the blank. Since much time and efforts are required to manufacture the rigid die with various geometries, FE simulation is adopted as the major tool to investigate the effect of process parameters. The main process parameters such as the rubber hardness and the key geometric dimensions of the rigid die (the radius of curvature) are explored with the FE model.

(a)

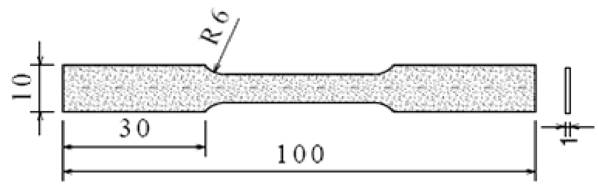
(b)

Fig. 2 (a) The equipments used for the rubber pad forming and (b) photos of formed parts

In this article, the non-linear approach is chosen because of the sheet plasticity and rubber hyper-elasticity during simulations that have highly non-linear behavior. By taking advantage of plane strain it is possible to simulate the form block, blank, and rubber assembly as a two-dimensional model. To model these materials through finite element method (FEM), a constitutive law based on total strain energy density W has to be adopted.

The interfaces between the die and the blank, and between the rubber and the blank, are modeled using an automatic surface-to-surface contact algorithm. The die is modeled as a rigid body. A coefficient of friction of (0.1 to 0.3) is used between the rubber and the blank. The values of coefficients of friction are based on historical data for similar cases (for example Dirikolu and Akdemir) [5].

Properties for the aluminum blank were determined from a tensile test performed on the blank material according to ASTM E 8M standard (Fig. 3).



(a)

(b)

Fig. 3 Dimensions of the aluminum specimen and photos of the specimens before and after the tensile test

Table 1 Mechanical properties of sheet metal

Density	E (GPa)	∂_y (MPa)	UTS(MPa)	ν
2700	67/12	124	178	0.33

The results of this experiment are listed in table 1. The material compression tests were also carried out according to ASTM D575 standard to determine the material properties of the rubber. In axial compression, a test piece becomes shorter and its cross section increases. Thus, the characteristics measured in compressive tests are the same as in tensile tests, but with an opposite sign construction instead of elongation and an increase of the cross-sectional area instead of its reduction [8]. The results of this experiment are shown in Fig. 4 and table 2.

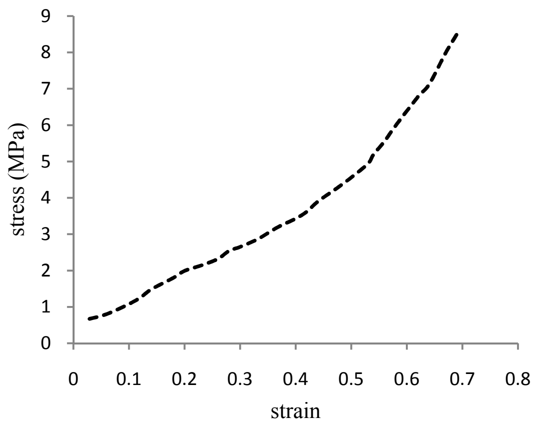


Fig. 4 Experimental compression stress–strain curve for natural rubber

Table 2 Mechanical properties of rubber pad

Shore	C10 (MPa)	C01 (MPa)	E (MPa)	ν
61	0.482	0.17	4.467	0.44

2.1. Simulation of flexible material and modeling requirements

Flexible materials are widely used as its physical properties offer good pressure relief in most situations. A flexible material is an open celled elastomeric and its constituent elastomercan undergo large and reversible elastic deformations. When the material reaches this level of compression, it is referred to as 'bottomed out' increasing the possibility of discomfort.

Viscoelastic materials can be defined as an intermediate combination of elastic solids and viscous liquids [9]. Viscoelastic have non-linear stress–strain characteristics for relatively large deformations.

Under such conditions, they are generally assumed as nearly incompressible during deformation and hyper-elastic model (Mooney–Rivlin) is used to describe its behavior [5].

The Mooney–Rivlin model adds a term that depends on the second invariant of the left Cauchy-Green tensor. This form will give amore accurate fit to the experimental data. It uses a strain energy function W, whose derivative with respect to a strain component determines the corresponding stress component.

The strain energy function of a hyper-elastic material can be expanded as an infinite series in terms of I_1 andI_2. To find the value of these two parameters in the simulation section we can use equations related to the issue. The parameters can be found through the results of the stress strain (Fig.4) and the following equations [10]. The strain energy function for the 2-parameter model is:

$$\sigma_{ij} = \frac{\partial W}{\partial \epsilon_{ij}} \tag{1}$$

$$w = \sum_{k+m-1}^{n} c_{km}(I_1-3)^k + (I_2-3)^m + \frac{1}{2}k(I_3-3)^2$$

Where 'W' is the strain energy per unit of reference volume; I_1, I_2 and I_3 are the strain invariants. 'k' is the bulk modulus and I_3=3 for incompressible material behavior. 'C_{km}' is the constant of the Mooney–Rivlin material model.

Usually two Mooney–Rivlin parameters(C_{10} and C_{01}) are used to describe hyper-elastic rubber deformation.C_{10} and C_{01} were calculated from below mentioned relations:

$$\begin{bmatrix} \sum_{j=1}^{n} \beta_1^2(\varepsilon_j) & \sum_{j=1}^{n} \beta_1(\varepsilon_j)\beta_2(\varepsilon_j) \\ \sum_{j=1}^{n} \beta_1(\varepsilon_j)\beta_2(\varepsilon_j) & \sum_{j=1}^{n} \beta_2^2(\varepsilon_j) \end{bmatrix} \begin{Bmatrix} C_{01} \\ C_{10} \end{Bmatrix} = A \tag{2}$$

$$A = \begin{Bmatrix} \sum_{j=1}^{n} \beta_1(\varepsilon_j)\sigma_j \\ \sum_{j=1}^{n} \beta_2(\varepsilon_j)\sigma_j \end{Bmatrix} \times 10^9 [\mathrm{Pa}]$$

where 'σ' is the stress, 'ε' is the strain and 'n' is the points of the stress strain diagram. These parameters can be determined by experiments. $\beta_1(\varepsilon_j)$, $\beta_2(\varepsilon_j)$ values can be obtained from Eqs. (3, 4)

$$\beta_1(\varepsilon_j) = 2\left(\varepsilon_j^2 - \frac{1}{\varepsilon_j^4}\right) \tag{3}$$

$$\beta_2(\varepsilon_j) = 2\left(\varepsilon_j^4 - \frac{1}{\varepsilon_j^2}\right) \tag{4}$$

The rubber has been modeled by using four-node HYPER56. The HYPER56 element is used for 2-D modeling of solid hyper-elastic structures. It is applicable to nearly incompressible rubber-like materials with arbitrarily large displacements and strains.

The element can be used either as a biaxial plane element (plane strain) element [11]. The plane strain option has two degrees of freedom at each node. The number of nodes and elements are 339 and 303, respectively.

Table 3 The type of the elements used in the simulation

Process tools	The type of the elements
Blank	Visco 106
Rubber pad	Hyper 56
Form block	Plane 42
container	Mesh 200

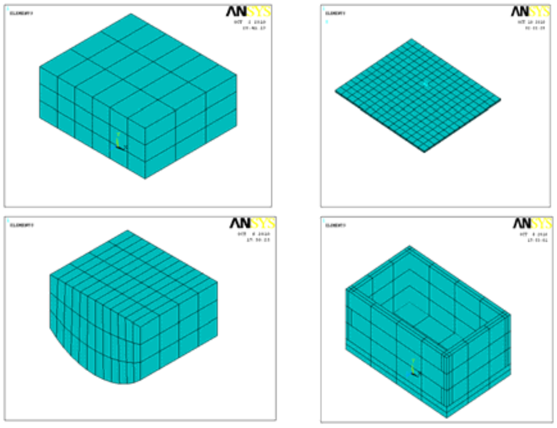


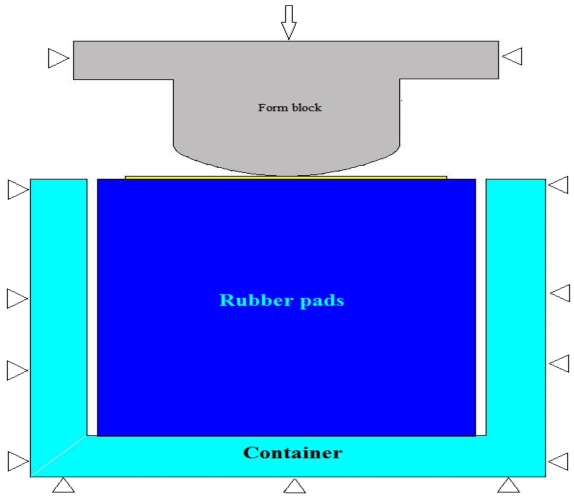
Fig. 5 The finite element model

The blank and the form block are modeled with visco106 and plane 42, respectively, that have plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. VISCO106 is used for 2-D modeling of solid structures. It can be used either as a plane strain element, and is defined by four nodes having up to three degrees of freedom at each node.
The element is designed to solve both isochoric (volume preserving) rate-independent and rate-dependent large strain plasticity problems and Plane42 is used for 2-D modeling of solid structures [11]. Based on the above considerations the model has been generated as shown in Fig. 5. The type of the elements used in the simulation is listed in Table 3.

3 RESULTS AND ANALYSIS

3.1. Validating finite element method

In order to evaluate the simulation results by finite element method, the analysis of this method was performed using the same geometry, material and loading conditions of the experiment. It is concluded that there is a satisfactory comparison between the modeling and experimental results.
Figs. 7 and 8 show comparative diagram between the experimental work and the simulation results of the applied force values (with radius of curvature 35 and 50, respectively).



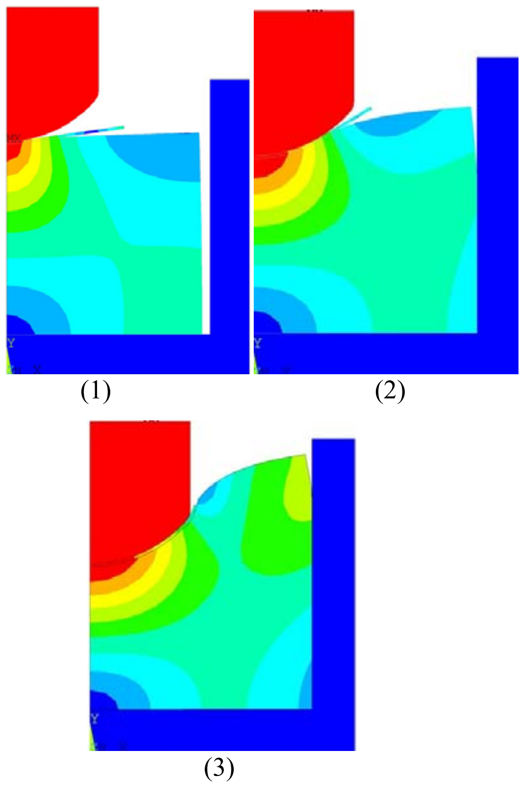


Fig. 6 2D finite element and the step-by-step forming processusing natural rubber, (1) rubber self deformation. (2) blank deformation (3) the final blank deformation

Using the above-mentioned points, it is suggested that the maximum error value for estimating prediction of the applied force to be about 6.48%.

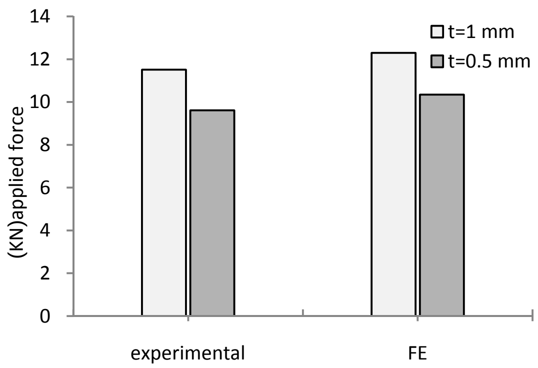


Fig. 7 Comparison of applied forcefor shaping the blank with variable thickness(radius of curvature 35 mm)

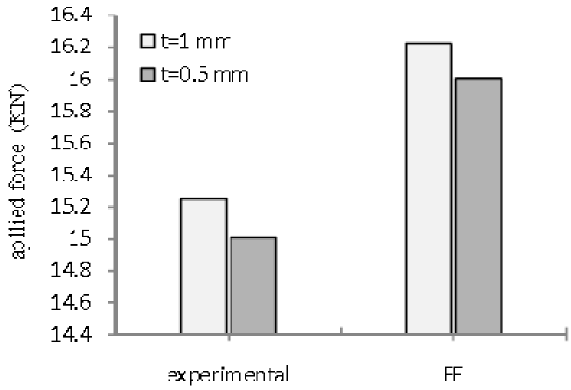


Fig. 8 Comparison of applied force for shaping the blank with variable thickness(radius of curvature 50 mm)

3.2. Effect of friction coefficient

The friction conditions include those parameters which effect on the flexibility and the quality of the produced samples. Changes due to friction may cause changes in the stress-strain distribution. The effect of friction atthe rubber pad-blank and blank-form block interfaces was studied by varying the friction coefficients. Overall, the bellow two friction interfaces are defined in this study:

f_1: The friction coefficient between the form block and metal sheet

f_2: The friction coefficient between the rubber pad and metal sheet

According to Dirikolu and Akdemir [5], the friction has been chosen between 0 and 0.3. Figs. 9 and 10 show the effect of friction coefficient variations on the maximum Van-Mises stressin simulation. The results show that by increasing f_1, the maximum stress will decrease. However, the friction coefficient f_2 has reverse role comparing to f_1. By increasing f_2, it can be seen that the maximum Van-Mises stress is increased. This could be due to lack or hardness in moving metal sheet toward form block.

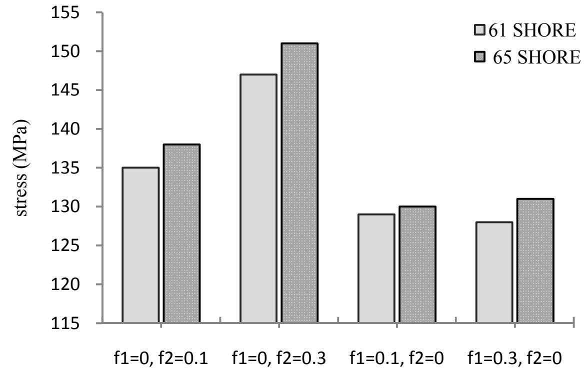


Fig. 9 Effect of friction coefficient variants on the maximum Van-Mises stress

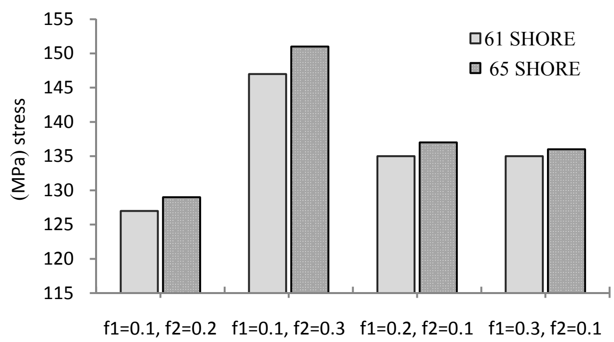


Fig. 10 Effect of friction coefficient variants on the maximum value of the Van-Mises stress

Table 4 The mechanical properties used for the simulation of rubber pad

Shore	C10 (MPa)	C01 (MPa)	E (MPa)
40	0.189	0.045	0.381
45	0.232	0.058	1.800
50	0.302	0.076	2.397
55	0.382	0.096	3.207
60	0.474	0.118	4.268
65	0.586	0.147	5.616
70	0.736	0.184	7.289

3.3. Effect of rubber hardness on load-stroke curve

Fig. 1 shows the punch load against the stroke of the punch(mm). The rubber material properties are shown in Table 4 [5, 12]. Results indicate that as the punch reaches 26mm, maximum applied force is indicated to be 17.187 KN. Using rubber with lower hardness, this value will drop to 9.972 KN. Using rubbers with less stiffness leads to partial formation of the production samples; therefore, while production cycle and press capacity are low, it is possible to use rubbers with less stiffness as flexible punch.

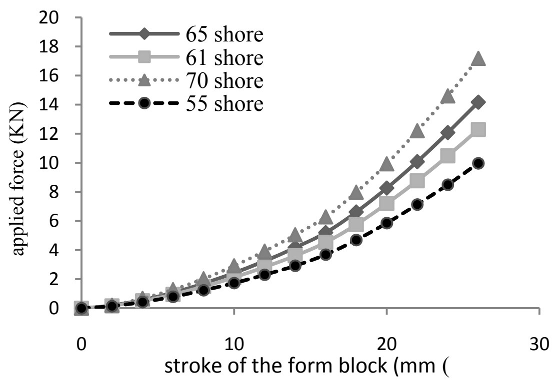


Fig. 11 Load-stroke curveusing rubber with different hardness (radius of curvature 35 mm)

3.4. Effect of rubber thickness

To investigate the effect of rubber thickness, eight rubbers with different thickness are used. Figure 13 shows the distribution of von-Mises stress at the full load application in the formed blank using different natural rubber-pad thicknesses. Referring to Fig. 12, it is possible to conclude that while the rubber thickness is low, this may lead to partial formation of the sample. Hence, it is necessary that the rubber thickness to be at least 2 to 2.5 times more than the necessary stroke in the process.

3.5. Spring back

Spring back is a common phenomenon in sheet metal forming which happens by redistribution of inner rubber tensions during loading. The ratio of the final bend angle to the initial bend angle is defined as the springback factor, K_S. The amount of springback depends upon several factors, including the material, bending operation, and the initial bend angle and bend radius [13]. The spring back factor (ks) can be obtained from Eq. (5)

$$k_s = \frac{\alpha_f}{\alpha_i} = \frac{\left(\frac{2r_i}{t}\right)+1}{\left(\frac{2r_f}{t}\right)+1} \quad (5)$$

Where r_i and r_f are bend radius before and after spring back, respectively and α_i and $\alpha_f$are bending angle before and after spring back, respectively.

In this part the result of experimental and simulation works is compared. To investigate the spring back, ten pairs of parts have been evaluated with the same thickness (1mm) and variable curvature radius of 35 and 50 mm. In order to measure this, the initial angle is in fact the vertex angle of the form block and the final angle by measuring the outer surface angle respectively. The result is shown in Fig. 13, where the maximum error for estimating the prediction of applied force is about 6.48%.

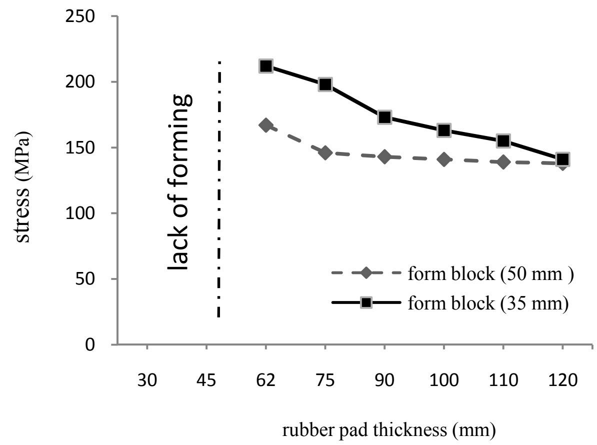


Fig. 12 Effect of rubber-pad thickness on the maximum Von-Mises stress

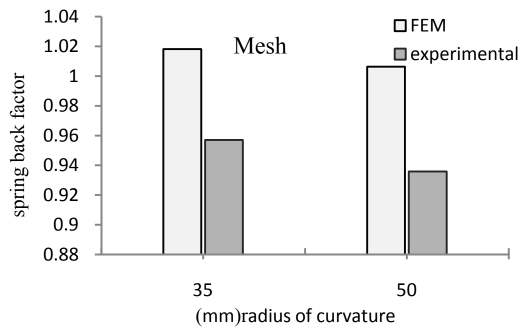


Fig. 13 FE results compared to simulation results

3.5.1. Effect of lubricabt on springback phenomenon

The effect of lubricant on the spring back phenomenon of the formed part is investigated numerically as well as experimentally. The results of this study are shown in Figure 14 where utilizing lubricants during forming process with rubber pad causes increase in spring back value. This could be due to decline in the created friction.

Therefore, the reduction of friction coefficient is a factor of reducing tensile stress exerted on the bend cross-section and thus the plastic bandwidth is reduced. In this part the effect of thinning in the formed sheet metal has been assessed numerically. The model has been divided into five different areas and each area is studied. In the end, the results of the changes made in reduction of thickness are presented.

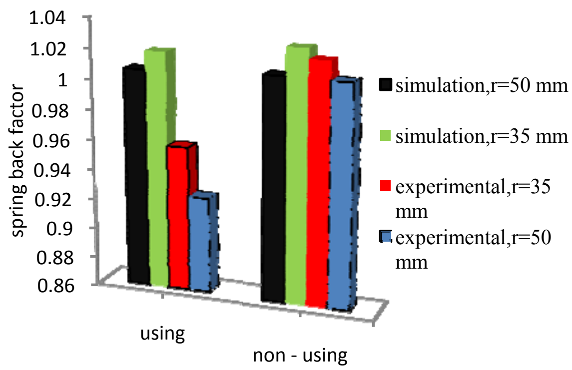


Fig. 14 Effect of using and not using lubricant on spring back, curvature radius of 35 and 50 mm

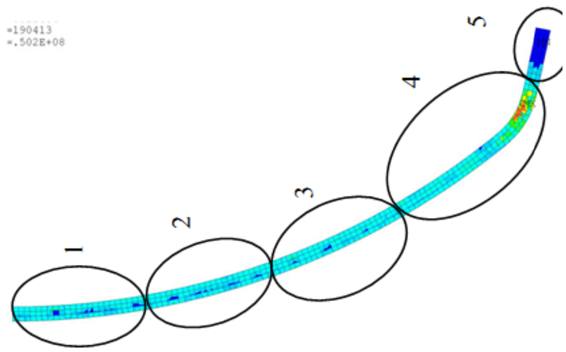


Fig. 15 Finite element model of the sheet metal and its divisions

These changes could be the result of variations in parameters such as rubber thickness and friction coefficient. Fig 15 indicates the finite element model of the metal sheet and its classification**.**

3.6.1. Effect of rubber thickness on thinning

To investigate the effect of rubber thickness on thinning, four rubbers with variable thickness are used and the rubber thickness is set constant (1mm). The result shows that when the rubber pad thickness is decreased, the amount of thinning is increased (Fig. 16). The amount of thinning with using of a rubber that has 120 mm thickness is 0.89 mm, while using a rubber thickness of 62 mm, the thinning is reached to 0.875 mm. Therefore using rubbers with greater thickness will decrease the thinning amount.

3.6.2. Effect of coefficient of friction on thinning

In this section,two friction interfaces are defined to investigate the effects of friction.The friction coefficients f_1 and f_2 are friction coefficients between the forming and metal sheet and between the rubber and metal sheet, respectively. Fig. 17 shows the amount of thinning at remarkable areas. When the friction coefficient within rubber sheet is increased, the amount of thinning is increased and when the friction between the forming and sheet is increased, it is helpful for sheet curvature and for this reason the amount of thinning decreased slightly.

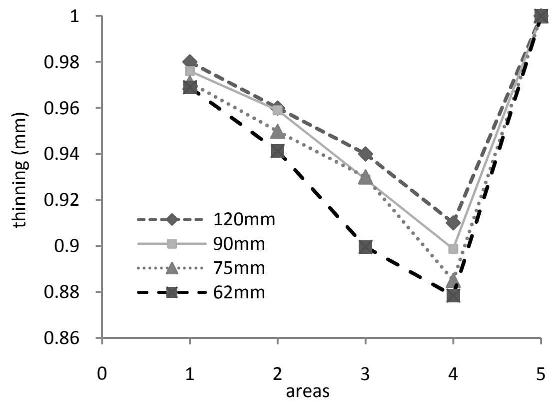


Fig. 16 Effect of rubber thickness variation on the thinning

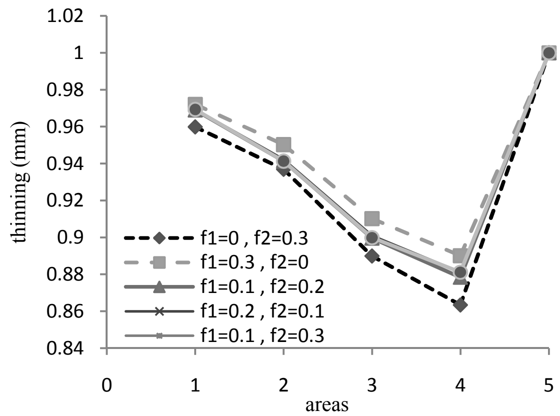


Fig. 17 Effect of coefficient of friction on the thinning

4 CONCLUSION

In this paper, the role of key parameters in the forming process using rubber pad, applied on the components with radius curvature is investigated experimentally and numerically. The forming parameters (curvature radius, sheet thickness, rubber pad thickness, rubber hardness, lubrication condition and spring-back phenomena) related to the forming process are investigated in detail. FE simulations were carried out in ANSYS to analyse the process. The FE prediction of the maximum error value for estimating prediction of the applied force is compared with experimental measurements to validate the FE model. The main findings of this research are summarized below:

1) Using FE simulation, it is possible to gain a true and better understanding of the forming process; using this, as an effective and cost effective approach, it enables to determine and analyze important process parameters. Error analysis of the results indicates that it is possible to use FE approach for modeling of this process with a very good approximation on the samples having radius curvatures. The error of estimating the applied force is about 6.4%.

2) Friction coefficient is an effective parameter on the process improvement and quality of the formed parts. When the friction between the form block and sheet metal is increased, this helps the sheet bending. Therefore, by creating an appropriate condition of the friction between the surface of rubber-sheet and also sheet-form block, the quality and formability of the formed parts is increased.

3) The rubber thickness is also recognized as an effective parameter on the present method of metal forming process. The increase in rubber thickness causes reduction in the spring back and thinning effect. As the rubber-pad thickness decreases, the amount of thinning is increased.

4) Simulations demonstrate the influence of lubricanton the spring back value.

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REFRENCES

[1] Myuang, j., “Stretch forming analysis for skin of aircraftAerospace”, Korean, 2001.

[2] Thiruvarudchelvan, S., “The potential role of flexible tools in metal forming”, J. Mater. Process. Technol. 122, 2002, pp. 293-300.

[3] Browne, D. J. and Battikha, E., “Optimisation of aluminium sheet forming using a flexible die”, J. Mater. Process. Technol. 55, 1995, pp. 218-223.

[4] Dirikolu, M. H., and Akdemir, E., “Computer-aided modelling of flexible forming process”, J. Mater. Process Technol. 148, 2004, pp. 376-38.

[5] Ramezani, M., Ripin, Z. M., and Ahmad, R., “Computer aided modelling of friction in rubber-pad forming process”, J. Mater. Process Technol.209, 2009.

[6] Peng, L., Hu, P., Lai, X., Mei, D., and Ni, J., “Investigation of micro/meso sheet soft punch stamping process –simulation and experiments”, J. Mater, Vol.30, 2009, pp.783-790.

[7] “Standard test method for tension testing of Metallic Materials”, Designation, E 8M -04.

[8] khoshkish, H., “Taghipour & Narimani, Application of rubber pad forming in automotive parts Prototyping”, Proceeding of the International Manufacturing Leaders Forum Adelaide, Australia 2002.

[9] Mooney, M. A, “Theory for large elastic deformation”, J. Appl. Phys. 11, 1940, pp.582-597.

[10] ANSYS Theory Manual for Release 5.6, 11th Edition, ANSYS Inc., November, 1999.

[11] www.engineeringpolymers.com

[12] Wei, G., and Wagnor, R. H., “Die design method for sheet springback”, International Journal of Mechanical Sciences, Vol. 46, 2004, pp. 1097-1113.