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Prediction and optimization of thinning in automotive sealing cover using Genetic Algorithm

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Abstract

Deep drawing is a forming process in which a blank of sheet metal is radially drawn into a forming die by the mechanical action of a punch and converted to required shape. Deep drawing involves complex material flow conditions and force distributions. Radial drawing stresses and tangential compressive stresses are induced in flange region due to the material retention property. These compressive stresses result in wrinkling phenomenon in flange region. Normally blank holder is applied for restricting wrinkles. Tensile stresses in radial direction initiate thinning in the wall region of cup. The thinning results into cracking or fracture. The finite element method is widely applied worldwide to simulate the deep drawing process. For real-life simulations of deep drawing process an accurate numerical model, as well as an accurate description of material behavior and contact conditions, is necessary. The finite element method is a powerful tool to predict material thinning deformations before prototypes are made. The proposed innovative methodology combines two techniques for prediction and optimization of thinning in automotive sealing cover. Taguchi design of experiments and analysis of variance has been applied to analyze the influencing process parameters on Thinning. Mathematical relations have been developed to correlate input process parameters and Thinning. Optimization problem has been formulated for thinning and Genetic Algorithm has been applied for optimization. Experimental validation of results proves the applicability of newly proposed approach. The optimized component when manufactured is observed to be safe, no thinning or fracture is observed.

Keywords: Thinning; Prediction; DOE; Regression

1. Metal forming – Introduction

Sheet metal forming is a significant manufacturing process for producing a large variety of automotive parts, aerospace components as well as consumer products (kitchen sinks, cans, boxes, etc.). These are broadly classified as forming/drawing/stamping and deep drawing operations, which include a wide spectrum of operations and flow conditions. Deep drawing is a compression-tension forming process [1]. With the greatest range of applications involving rigid tooling, draw punches, a blank holder and a female die. In this process the blank is generally constrained over the draw punch into the die to give required shape of cavity.

The sheet material is subject to a large plastic deformation combined with a complex flow of material. Design in sheet metal forming, even after many years of practice, still remains more an art than science. This is due to the large number of parameters involved and their interdependence. These are material properties, machine parameters such as tool and die geometry, work piece geometry and working conditions. Research and development in sheet metal forming processes requires lengthy and expensive prototype testing and experimentation in arriving at a competitive product.

In deep drawing of a cup the metal is subjected to three different regions of deformations. Fig. 1 represents the deformation and stresses developed in a pie-shaped section. The metal at the center of the blank under the head of the punch is wrapped

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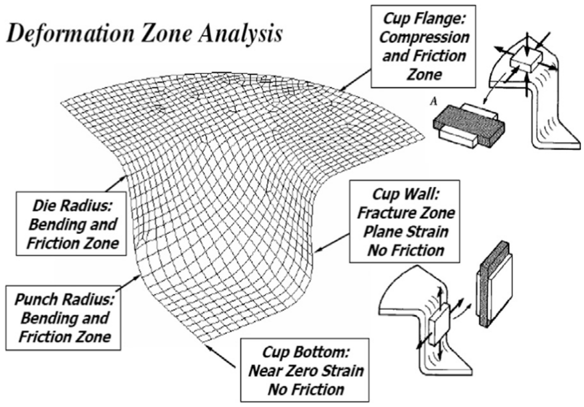

Fig. 1. State of stress in deep drawing.

around the profile of the punch. The metal in this region is subjected to biaxial stress due to the action of the punch. The metal is bent over the Punch Radius which causes friction. At the center of cup there is no strain and no friction. Metal in the outer portion of the blank is drawn radially inward towards the throat of the die [2]. However, as the metal passes over the die radius, it is first bent and straightened, while at the same time being under tensile stresses, this causes considerable friction. As it is drawn in, the outer circumference must continuously decrease from that of the original blank, to that of the finished cup. This means that it is subjected to a compressive strain in the circumferential or hoop direction and a tensile strain in the radial direction.

As a result of these two principal strains, there is a continual increase in the thickness as the metal moves inward in the flange region. This plastic bending under tension results in considerable thinning; this modifies the thickening due to the circumferential shrinking. The proposed innovative methodology combines two techniques for optimization of thinning in automotive sealing cover. Taguchi design of experiments and analysis of variance is used to analyze the influencing process parameters on thinning. Mathematical relations have been developed to relate input process parameters and thickness reduction. Optimization problem has been formulated and Genetic Algorithm is applied for optimization. There are a lot of Evolutionary and Bio Inspired optimization algorithms available nowadays, such as Particle Swarm Optimization, Ant Colony Optimization, etc. Genetic Algorithm has its own advantages and capabilities which have been discussed in the following sections.

2. Major influential parameters

Four major process variables have been studied in Numerical Investigations for Sealing Cover to understand the effects of these parameters and their interaction on thinning. These are blank holder force, lubrication condition i.e. coefficient of friction, die profile radius and punch nose radius.

2.1. Lubrication

Lubrication is normally expressed in terms of coefficient of friction. In deep drawing all areas where sheet and tool slide are relative to each other and plastic deformation occurs with complex state of friction [3]. The sheet is stretched over the stamp; in this case the friction between the stamp and the sheet to a large extent determines the deformation. In some positions where the sheet slides over the edge of the die with a simultaneous shearing of the sheet material, the friction between die and sheet influences the coefficient which is assumed between 0.05 and 0.15. Schey [4] distinguishes a total of six contact and friction regions in deep drawing. Too low a friction involves a poor control of the sheet flow, because sheet will flow easily with a risk of wrinkling. While too high a friction leads to a risk of crack formation, because the slow movement of sheet can result into tearing and cracking.

2.2. Blank holding force

The blank holder force is applied to control the flow of material in the die. Blank holder force has significant contribution on the product quality. Appropriate blank holder force evolved through a process results in controlling the thickness variations in a deep drawn part and thus the quality of the part. An optimal blank holder force eliminates wrinkling as well as tearing, the two major phenomena that cause failure in formed parts. During numerical investigations, a constant blank holder force is applied during a forming process to minimize mechanisms in the forming tools.

2.3. Punch nose radius

The draw punch applies the required force onto the sheet metal blank in order to cause the material to flow into the die cavity. The critical features of the draw punch include the punch face and Punch Nose Radius. Punch Nose Radius cannot be too small as it will try to pierce or cut the blank rather than force the material to bend around the radius [5]. The minimum punch-nose radius depends on material type and thickness. It is equally important to understand that, as the punch-nose radius is increased the blank will tend to stretch on the punch face rather than draw-in the blank edge.

2.4. Die profile radius

The die profile radius and die-face surface are probably the most influential features in a draw tool that uses a flat blank holder [6]. If the draw radius is too small the part may split as the material deforms. This is due to the high restraining forces caused by bending and unbending of the sheet metal over a tight radius. Drawing over a tight radius also produces a tremendous amount of heat. This can lead to microscopic welding of the sheet metal to the tools, known as galling. On the other hand, an excessive die radius causes the blank to wrinkle in the unsupported region between the punch face and the die face. It is apparent that there must be some range of die radii to select from that will work; not too small and not too big.

3. Thinning

Deep drawing is a high order non-linear problem in numerical modeling [7]. The thinning refers to reduction in thickness than the original thickness of blank at various cross sections of the components. The conventional deep drawing process is limited to a certain Limit Drawing Ratio (LDR), beyond which localized wall thinning and rupture occur. One way to increase the LDR is to try to capture the onset of necking and to adjust process parameters in order to delay or avoid necking [8]. The limiting drawing ratio decreases as sheet thickness decreases and it decreases rapidly below 0.04 mm thickness [9]. Prediction of the forming results, determination of the thickness distribution and the thinning of the sheet metal blank will decrease the production cost through saving material and production time [10]. In this research thinning is measured from the simulation results of thickness at various cross sections, where it has reduced than that of original, and average reduction in thickness is calculated. Average reduction in thickness is used for analysis of variance.

4. Sealing cover – automotive component under investigations

Sealing cover is manufactured by Vishwadeep Enterprises, Chikhali, Pune, for Dali and Samir Engineering Private Limited. It is fitted to two wheeler petrol tank. The configuration of sealing cover is very simple, but quite different from typical cup. It is having large diameter to height ratio and there is no flange (Figs. 2 and 3).

The base has a curvature with 150 mm radius. The cup diameter is of 58.6 mm and total height is 09 mm. The base corner radius is of 2 mm. The material is SPCC and it is a drawn component, where diameter to depth ratio is very high.

5. Proposed methodology

A. Numerical experimentation is carried out with Taguchi Design of Experiments involving input parameters and performance measure as thickness reduction.
B. Analysis of variance is carried out to predict the effect of input parameters on thickness distribution. Sensitive parameters are identified.
C. Regression is applied for mathematical modeling. This is the major contribution of authors.

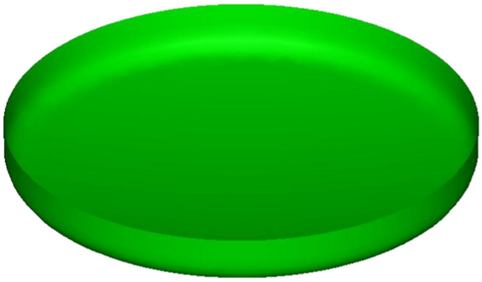

Fig. 2. Sealing cover.

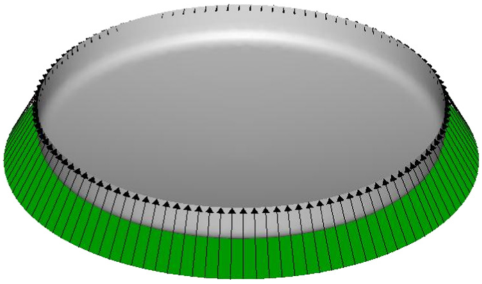

Fig. 3. Sealing cover – edge displacement.

D. Optimization problem is formulated and Genetic Algorithm is applied. The Process variables have been selected with extensive literature survey and the lower and upper bounds have been decided with industry manufacturing them. Optimum combination of parameters is applied in numerical simulation after optimization using Genetic Algorithm. So it is the most effective combination of parameters.
E. The results of optimization are validated with experimental results.

6. Taguchi experiments – orthogonal arrays

The Taguchi design of experiments involves reducing the variation in a process through robust design of experiments. The Taguchi method was developed by Dr. Genichi Taguchi of Japan. Taguchi developed a method for designing experiments to investigate how input parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations [11].

This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. During present investigations for sealing cover, four parameters are selected as blank holder force [BHF], lubrication-coefficient of friction [μ], punch nose radius [R_P] and die profile radius [R_D]. Three levels of each parameter are selected. Taguchi suggests L9 orthogonal array for four parameters and three levels. The design along with three levels of parameters is presented in Table 1 [12].

7. Numerical investigations

Numerical simulations of sheet metal forming processes, based on finite element method (FEM), represent a powerful tool for prediction of forming processes and are used worldwide [13]. Numerical simulations have been carried out for all nine designed experiments using Forming Suite. Forming Suite is a popular solver for metal forming from Forming Incorporations,

Table 1
L9 Orthogonal array for sealing cover.

	Lower	Middle	Higher
BHF	02 kN	03 kN	04 kN
μ	0.05	0.10	0.15
RD	1.5 mm	2.0 mm	2.5 mm
RP	6.0 mm	7.0 mm	8.0 mm

Expt. no.	**Blank holder force**	**Coefficient of friction**	**Die profile radius**	**Punch nose radius**
1	02	0.05	1.5	6.0
2	02	0.10	2.0	7.0
3	02	0.15	2.5	8.0
4	03	0.05	2.0	8.0
5	03	0.10	2.5	6.0
6	03	0.15	1.5	7.0
7	04	0.05	2.5	7.0
8	04	0.10	1.5	8.0
9	04	0.15	2.0	6.0

Canada. One of the major reasons of rejection in deep drawn parts is due to thinning and then fracture or cracks. Therefore, the thickness distribution is measured in numerical experiments as response. Following figures elaborate the state of thickness in all experiments designed. Original thickness of sealing cover is 0.8 mm, whereas maximum thickness is observed to be 0.847 in experiments one and four. The minimum thickness observed is 0.767 mm in experiment nine. All the experiments show more or less thinning behavior. The various colored bands show various thickness ranges. The average thickness in thinning region is measured as shown in Table 2 (Fig. 4).

8. Analysis of variance

To establish the relationships between investigated process parameters and thinning effect, analysis of variance is carried out after numerical experimentation. Signal to noise ratio measures quality with emphasis on variation of process [14]. The *S*/*N* ratios were calculated for minimizing the thinning, criterion selected is minimum the better. The formula applied is

$$S/N = -10 \log \text{[Sum of square of[Original Thickness–Reduced Thickness]} \tag{1}$$

Table 2 represents the thickness distribution for all experiments in simulations of Sealing Cover.

The minimum thickness observed is 0.785 mm in second experiment. The mean *S*/*N* ratios were calculated for all parameters blank holder force, coefficient of friction, die profile radius and punch nose radius at all three levels low, medium and high as shown in Table 3. The range is defined as the difference between maximum and minimum value of *S*/*N* ratio for particular parameter. Higher the range higher is the rank indicating that the parameter is more sensitive and influential on response. The results of orthogonal array indicate that friction has major influence on thinning. Punch nose radius has second rank; blank holder force has third rank and die profile radius has least influence.

Table 2
S/*N* ratios for sealing cover.

Expt. no.	Decreased thickness (mm)			Average thickness (mm)	Thickness difference (MM)	*S*/*N* ratios
1	0.784	0.793	0.797	0.791	0.008	41.24
2	0.793	0.789	0.773	0.785	0.015	36.47
3	0.780	0.790	0.794	0.788	0.012	38.41
4	0.792	0.797	—	0.794	0.005	45.19
5	0.782	0.790	0.795	0.789	0.011	39.17
6	0.790	0.780	0.786	0.786	0.013	37.39
7	0.792	0.796	0.787	0.791	0.008	41.58
8	0.794	0.790	—	0.792	0.008	41.93
9	0.795	0.790	0.785	0.790	0.010	40.00

9. Problem formulation

Deep drawing process shows non-linear behavior. But the component under study is not deep drawn; the depth as compared to diameter is very less, so linear relationship has been applied. Eq. 2 below is the relation between four input parameters and reduction in thickness as performance measure, which is established using regression analysis. Minitab is used for linear regression [15].

$$\mathbf{THINNING = 0.795 - 0.000133\ BHF + 0.243\ \mu - 0.00033\ RD - 0.00217\ RP} \tag{2}$$

An optimization problem has been formulated with the following constraints.

Minimize F,

$$F = \text{THINNING} = 0.795 - 0.000133\ \text{BHF} + 0.243\mu - 0.00033\ \text{RD} - 0.00217\ R$$

$$\text{Subjected to } 1.2 \le \beta \le 2.2 \tag{3}$$

$$3R_D \le R_P \le 6R_D \tag{4}$$

$$F_{d\ Max} \le \pi d_m S_0 S_u \tag{5}$$

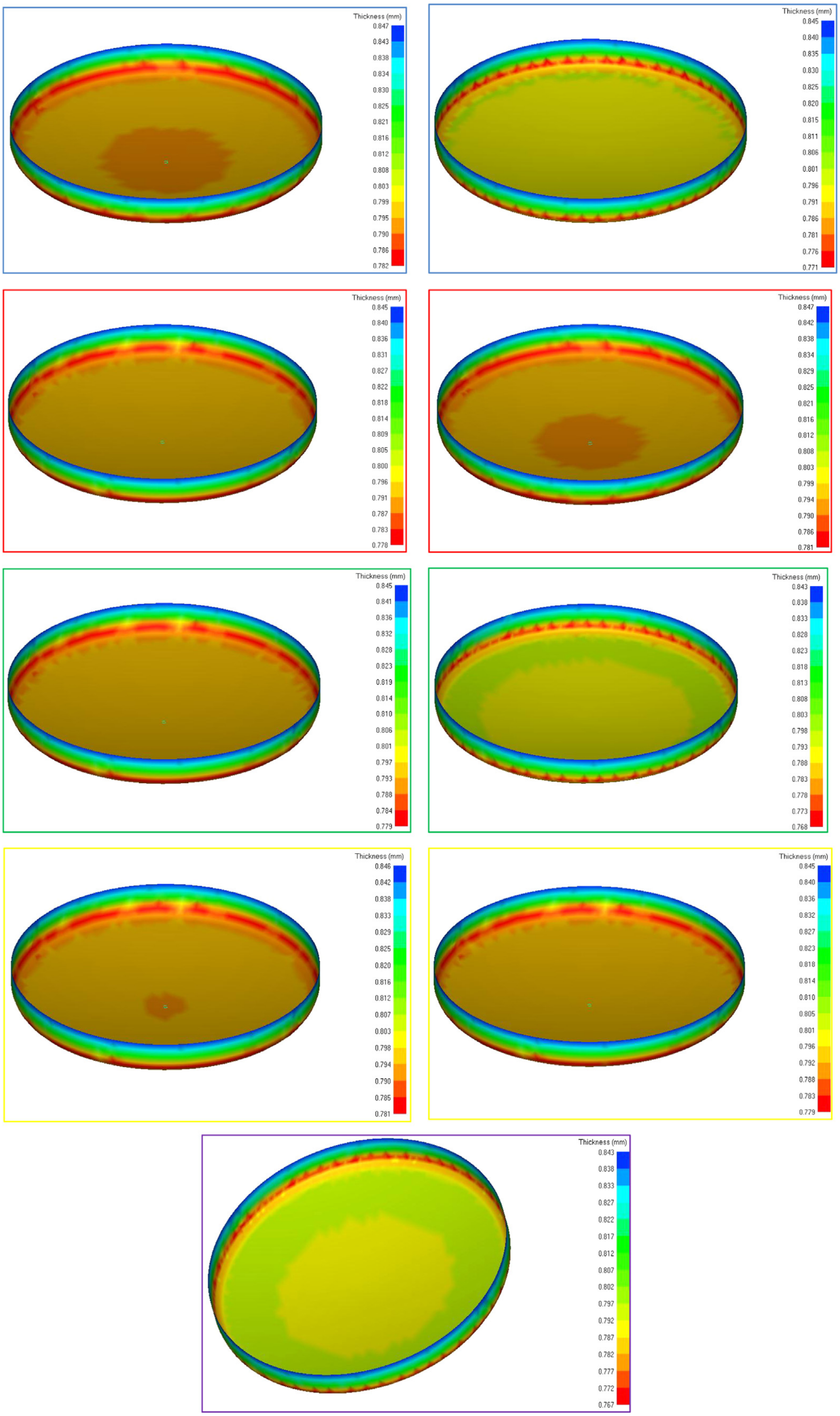

Fig. 4. Sealing cover – thickness distribution in nine experiments.

Table 3
Analysis of variance.

	BHF	Friction	RD	RP
1	38.71	42.67	40.19	40.13
2	40.58	39.19	40.55	38.48
3	41.17	38.60	39.72	41.73
Range	2.46	4.06	0.832	3.24
Rank	3	1	4	2

$$R_D \geq 0.035[50+(d_0-d_1)]\sqrt{S_0} \qquad (6)$$

The constraints have been applied to that of Draw Ratio which should be in between 1.2 and 2.2. The punch nose radius must be greater than three times and lower than six times that of die profile radius. The relationship between die profile radius, draw radius, blank diameter and sheet thickness must be satisfied. The condition for cracking should also be satisfied.

10. Optimization with genetic algorithm

Genetic Algorithm is a computerized search and optimization method based on the mechanics of natural genetics and natural selection [16]. Genetic Algorithm mimics the principle of natural genetics and natural selection to constitute search and optimization procedures. Professor John Holland of the University of Michigan, Ann Arbor envisaged the concept of these algorithms in the mid sixties. Genetic Algorithm combines survival of the fittest among string structures with a structured yet randomized information exchange, with some of the innovative flair of human research. In every generation, a new set of artificial creatures is created using bits and pieces of the fittest; an occasional new part is tried for good measure. Genetic Algorithm employs a form of simulated evolution to solve difficult optimization problems. Genetic Algorithm has a lot of benefits over traditional techniques. It is a proven tool as compared to newly coming Bio Inspired techniques. It works with population, so simultaneous processing is done and no potential global solution is neglected. It handles continuous as well as discontinuous functions with same efficiency. The solution never traps in local optima with Genetic Algorithm. Genetic algorithms work with string-coding of variables instead of variables. Coding discretizes search space.

Genetic Algorithm is applied for optimization of thinning. Blank Holder Force which is in turn function of punch diameter; friction coefficient and punch nose radius were kept as variables. For blank holder force relations from literature have been used. MatLab has been used for Programming. The Genetic Algorithm parameters are shown in Table 4 and variables ranges along with the optimization results are presented in Table 5.

Punch diameter, friction and punch nose radius have been set as variables and their bounds are presented in Table 5. The optimization results indicates that, with proposed approach, if optimum punch diameter is selected as 61 mm and friction coefficient as 0.15, and punch profile radius as 7.5 mm thinning can be restricted at 0.790 mm.

Table 4
GA parameters.

MOGA optimization parameters	
Population	Double vector
Selection	Tournament
Crossover	Two point
Mutation	Constraint dependent
Migration	Foreward
Crossover probability	0.80
Pareto front fraction	0.65
Stopping criterion	Number of generations
Generations	500
Initial population	300

Table 5
Results of optimization.

MOGA results			
Parameter	Lower bound	Upper bound	Optimum
Punch dia.	59 mm	61 mm	61 mm
Friction	0.05	0.15	0.15
Punch nose radius	06 mm	08 mm	7.5 mm
Thickness after thinning		0.790 mm	

11. Experimental validation and conclusions

To validate the results of numerical investigation, experiments were conducted with optimized parameters. The press used for experimentation is of 100 metric tons capacity; clutch operated, single acting mechanical power press of H-type. It is having steel body with bed size 680 mm by 680 mm. The bed to ram distance is 585 mm and stoke length is 125 mm. The prime mover for the press is an electric motor of 10 hp capacity. The shaft speed is 3680 rpm (Fig. 5).

Coefficient of friction was maintained as 0.15 using combined grease and oil mixture with full film lubrication. Punch was manufactured with optimized diameter and nose radius.

Experimental formability analysis was carried out for manufactured components and forming limit diagrams were plotted. Failure limit diagram is used for plotting the major and minor strains at every node in Finite Element Analysis and at every circle in experimental circle grid analysis. Circle grid analysis is performed on component by two methods; one is manual and other is using ARGUS Software and scanning. Circle grid analysis (CGA), also known as circle grid strain analysis, is a method of measuring the strain levels of sheet metal after a part is formed by stamping or drawing. A grid of circles of specific diameter is etched to the surface of the sheet metal. The forming process deforms the circles, stretching the diameters in one direction (the major strain) and compressing the diameters in the other direction (the minor strain). The difference between the major and minor diameters from the original diameter is the amount of strain. The manufactured

Fig. 5. Mechanical press and tooling.

Fig. 6. Circle grid analysis of manufactured components.

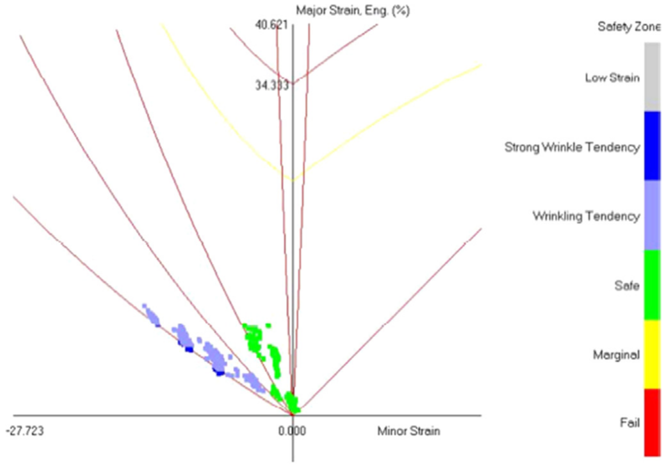

Fig. 7. FLD – experimental results.

components with optimum parameters with different configurations of circle grid are shown in Fig. 6. FLD shows safe points, marginal points and failed points along with failure and wrinkling curves on left side of vertical axis. The right-hand side of FLD represents stretch forming and equibiaxial strain. In drawing or deep drawing shearing and uniaxial tension occurs, which is represented on left-hand side. So in drawing or deep drawing, there are no points on right-hand side in FLD. The *X*-axis represents minor strain and *Y*-axis major strain. The FLD plotted below shows all the points in safe region, which indicates that there is no thinning; otherwise few points would have been appeared in fracture region, which would be failed points or may likely to fail, due to thinning and cracking.

The sealing cover manufactured with optimized parameters after experimental formability analysis was observed to be safely drawn without any thinning of failure. So it is concluded that the proposed optimization approach is successful and it is validated with experiments (Fig. 7).

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