Multi-objective optimisation of thickness and strain distribution for automotive component in forming process

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Abstract: Automotive manufacturing industry has emerged as one of the important facet of economy boost in developing countries like India. Globalisation, with invited competition, is demanding best quality products from manufacturer. Most of the parts of automotive, which contribute to safety and aesthetics, i.e., body parts are manufactured from sheet metal. Metal forming is complex, strain distribution process in formed part from flat blank involving range of processes from simple bending to deep drawing. Ideally the volume of the blank and formed component must remain constant, but decrease/increase in thickness of sheet metal is observed along with strains in major and minor direction. This results in various failures as wrinkling and fracture. The paper presents innovative methodology to distribute uniformly the thickness, preventing thinning/thickening. Multi-objective optimisation problem has been framed with two contradictory objectives as thinning and thickening correlating the process variables. Petrol tank cover, automotive component has been selected for study and numerical experimentation, from Vishwadeep Enterprises, Pune. Multi-objective genetic algorithm [MOGA] has been applied for process optimisation. The results obtained are encouraging and avoids thinning/thickening and results in uniform distribution of thickness in all sections of petrol tank cover.

Keywords: optimisation; metal forming; thickness; strain; automotive; Taguchi.

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1 Introduction to forming/drawing of sheet metals

Drawing is process of restraining sheet metal, called as blank at the edges, and the central portion is forced by a punch into a cavity to stretch the metal into a cup shaped drawn part. Mostly drawn parts are circular, rectangular or just about any cross-section. Amount of deformation defines drawing as shallow or deep. Shallow drawing is used to describe the process where the depth of draw is less than the smallest dimension of the opening; otherwise, it is termed as deep drawing (Zhang et al., 2004). It is comparatively easy to draw round shapes, i.e., cylindrical than square shapes. Other shapes can be produced at the cost of complexity of tooling and part costs. Deep drawing uses radial tension-tangential compression to shape the metal. Metal flowing is complex process to control, the uniform flow and strain distribution is key indicator of successful process. It is governed by many parameters. However, regardless of the many factors involved, the most important element to a successful deep drawing operation is initiating metal flow. The key elements affecting metal flow are sheet material, material thickness, work hardening coefficient, plastic strain ratio, blank size and shape, part geometry, draw ratio, forming load, blank holder force and lubrication. Each of them should be considered when designing/drawing stamping dies (Kakandikar and Nandedkar, 2013). Thick materials hold good for deep drawing operations, as they have high volumes and can be stretched comparatively longer. Lubrication facilitates reduction in coefficient of friction allowing material to slide. The draw ratio must fall within acceptable limits to allow metal to flow.

2 Petrol tank cover

Petrol tank cover as shown in Figure 1 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 petrol tank cover is very simple, but quite different from typical cup. It is having large diameter to height ratio and there is no flange. This comes under the category of shallow drawing. In this case the movement of ram is very limited, which determines the deformation of material. The base has a curvature with 150 mm radius. The cup has diameter of 58.6 mm and total height is 9 mm. The base corner radius is 2 mm. The material details are tabulated in Table 1.

Figure 1 Petrol tank cover (see online version for colours)

Table 1 Details of petrol tank cover

Manufactured by	Vishwadeep Enterprises, Pune
Component of	Dali and Samir Engineering Private Ltd.
Part no.	J-019
Weight	28 grams
Material	D-513, SS 4010, UST 1203
Thickness	0.8 mm
Yield strength	192 mega Pascal
Ultimate tensile strength	315 mega Pascal
r	1.7 min
n	0.22
Material model	Anisotropic

3 Proposed methodology

To optimise the forming process to manufacture petrol tank cover innovative methodology is proposed and discussed in detail in coming sections, the results are very appreciating.

1 The quality of products manufactured in sheet metal forming depends on distribution sheet thickness, which in turn depends on distribution of major strain and minor strain.

  So ultimate aim of research is to optimise performance measure – thickness distribution by virtue of thinning and thickening as well as strain distribution.

2 To optimise the manufacturing, process parameters needs to be studied. From literature four major parameters have been selected as blank holder force, friction, die profile radius and punch nose radius.

3 To understand the influence of these four process parameters on performance measure, experiments are designed by using Taguchi approach of L9 fractional orthogonal array.

4 Analysis of variance is carried out to identify sensitive parameters.

5 Based on outcomes of Taguchi design and analysis of variance, mathematical modelling is done to establish linear relationship between thinning, thickening and process parameters by regression.

6 Multi-objective optimisation problem is formed using these relationships and constraints from process.

7 Multi-objective genetic algorithm (MOGA) is applied for optimisation of process.

3.1 Process parameters

Four major dominant variables have been selected for Taguchi design of experiments after literature study and its critical review. These variables and their effects on end result of process are presented in following section.

3.1.1 Blank holder force

During drawing process, the blank is likely to develop defects if process parameters are not selected properly. Appropriate blank holder force evolved through a process results in controlling the thickness variations in a drawn part. An optimal blank holder force eliminates wrinkling as well as tearing, the two major phenomena that cause failure in formed parts. Generally, a constant blank holder force (Gantar et al., 2005; Yagami et al., 2007) is applied during a forming process to minimise mechanisms in the forming tools.

3.1.2 Friction

Friction plays an important role in drawing process. The friction conditions in the contact area of tool and sheet in metal forming are usually described by the friction coefficient μ according to Coulomb. It affects the boundary frictional (shear) stresses and modifies the strain distribution across the product quite considerably. The applied lubricants depend on the friction state (Kakandikar and Nandedkar, 2018). The friction state in deep drawing is a major factor that causes the increase of forming forces and tool wear, and may lead to defects.

3.1.3 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. If the draw radius is too small the part may split as the material deforms (Chandra Mohan Reddy et al., 2010; Chen and Liao, 2002). This is due to the high restraining forces caused by bending and unbending of the sheet metal over a tight radius. 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.

3.1.4 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. 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 (Jawad and Mohamed, 2008; Kakandikar et al., in press). A large radius, especially one that is highly polished, reduces the amount of friction on the punch-face surface.

4 Taguchi design of experiments

Four major influencing parameters blank holder force, coefficient of friction, die profile radius and punch nose radius were selected for the Taguchi design of experiments. Every process variable has three levels for operation as low, medium and high (Asgari et al., 2005). The orthogonal array selected for this combination of four parameters and three levels is L9 (Wei and Yuying, 2008). Table 2 presents the detailed L9 orthogonal array. Table 3 shows the parameters and three levels of them.

Table 2 Petrol tank cover – L9 orthogonal array

Expt. no.	*Blank holder force [KN]*	*Coefficient of friction*	*Die cushion radius [mm]*	*Punch nose radius [mm]*
I	4	0.10	1.5	6.0
II	4	0.15	2.0	8.0
III	4	0.20	2.5	10.0
IV	6	0.10	2.0	10.0
V	6	0.15	2.5	6.0
VI	6	0.20	1.5	8.0
VII	8	0.10	2.5	8.0
VIII	8	0.15	1.5	10.0
IX	8	0.20	2.0	6.0

Table 3 Petrol tank cover – three levels of process parameters

	Lower	*Middle*	*Higher*
Blank holder force [KN]	04	06	08
Coefficient of friction	0.10	0.15	0.20
Die cushion radius [mm]	1.5	2.0	2.5
Punch nose radius [mm]	06	08	10

5 Numerical experimentation and results

5.1 Thickness distribution

The original thickness of petrol tank cover is 0.8 mm. It is observed during experimentation that there is thinning as well as thickening behaviour. The thickness ranges for nine experiments are presented in Table 4.

Table 4 Petrol tank cover – thickness distribution

Expt.-I	0.78–0.84 mm	Expt.-II	0.77–0.84 mm	Expt.-III	0.77–0.84 mm
Expt.-IV	0.78–0.84 mm	Expt.-V	0.77–0.84 mm	Expt.-VI	0.76–0.84 mm
Expt.-VII	0.78–0.84 mm	Expt.-VIII	0.77–0.84 mm	Expt.-IX	0.76–0.84 mm

Figure 2 Thickness distribution in nine numerical experiments (see online version for colours)

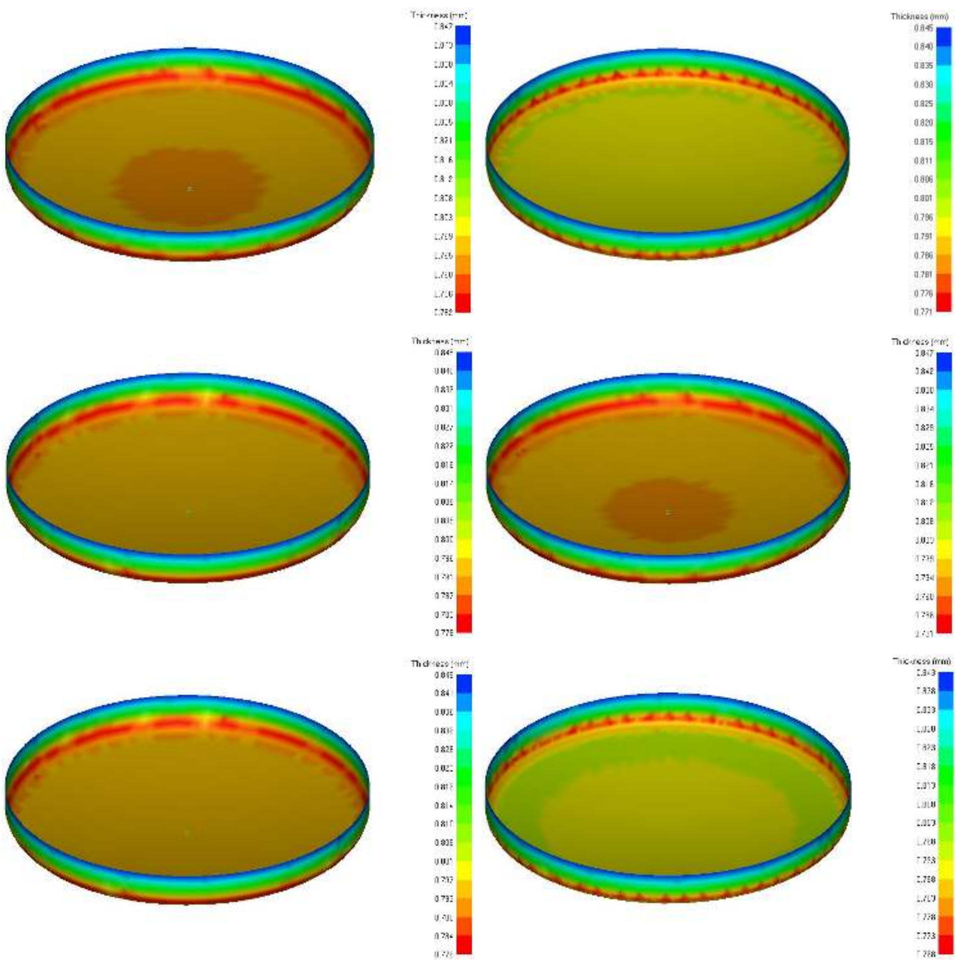
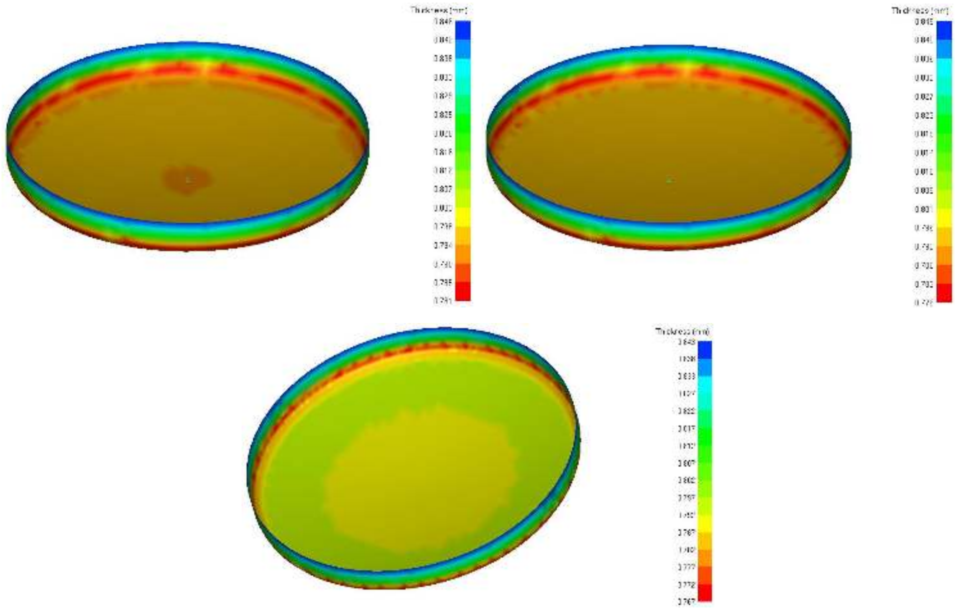


Figure 2 Thickness distribution in nine numerical experiments (continued) (see online version for colours)



5.2 Major strain distribution

The scale for percentage engineering major strain plotted in experiments ranges from 0% to 30%. It is observed that maximum strain observed during nine experiments is 13.02% and minimum is 9.13%. For most of the experiments, strain is 11.06%. The values of maximum strain recorded in nine experiments are presented in Table 5 and Figure 3.

Table 5 Petrol tank cover – major strain [engineering %]

Expt.-I	11.06%	Expt.-II	11.06%	Expt.-III	13.02%
Expt.-IV	9.13%	Expt.-V	11.06%	Expt.-IV	9.13%
Expt.-VII	11.06%	Expt.-VIII	11.06%	Expt.-IX	11.06%

Figure 3 Petrol tank cover – major strain in nine experiments (see online version for colours)

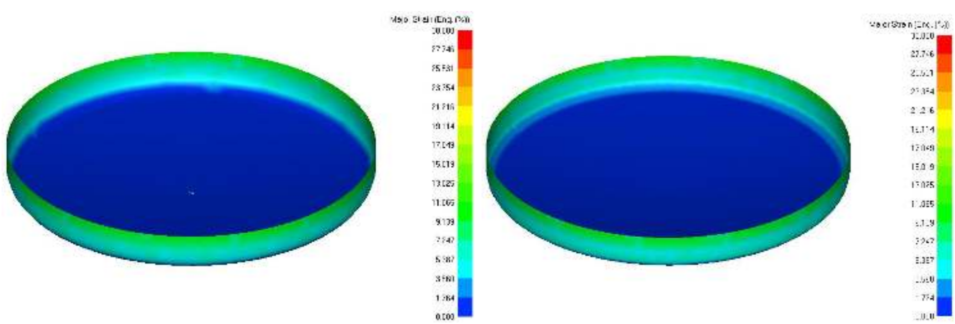
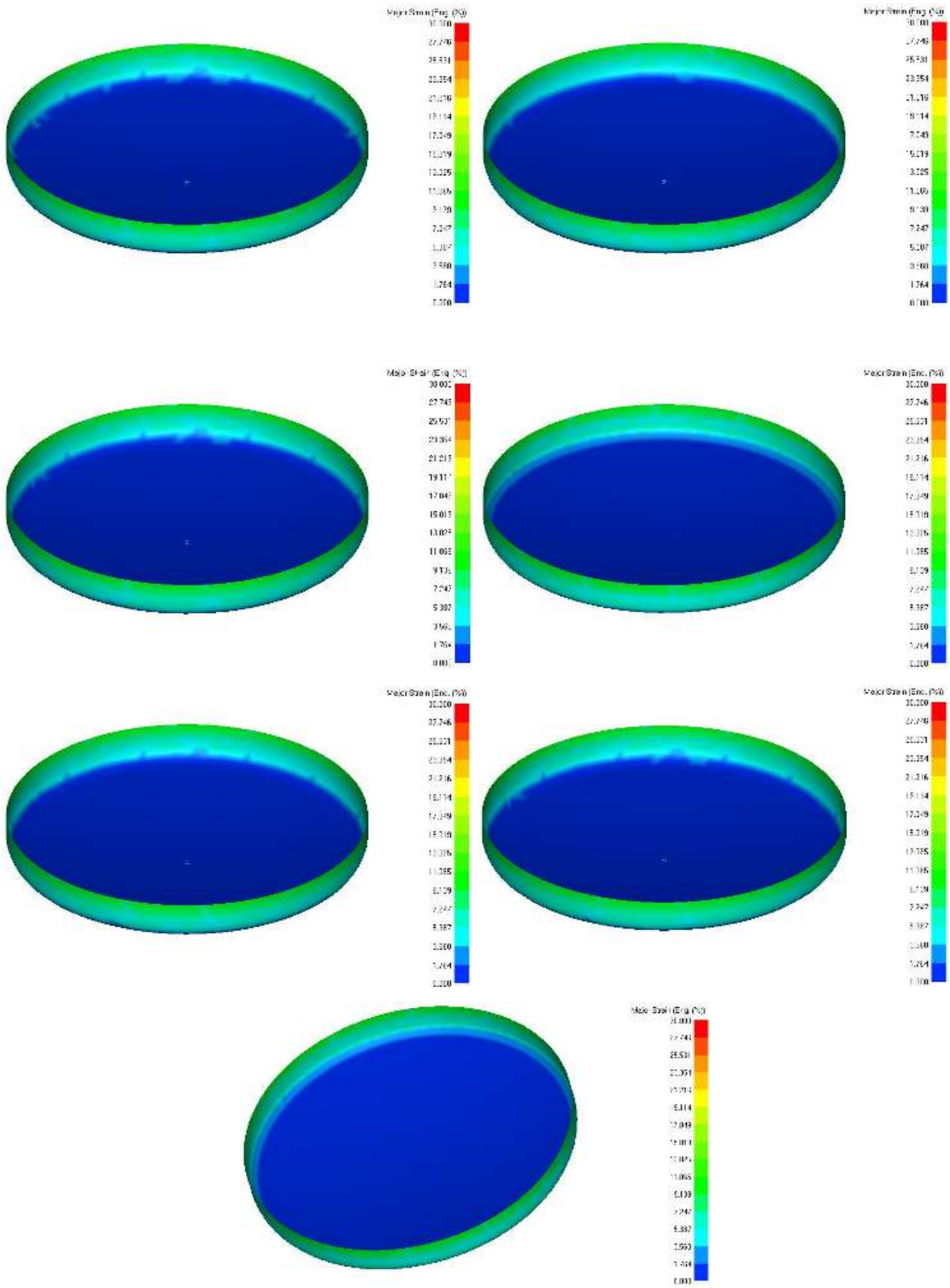
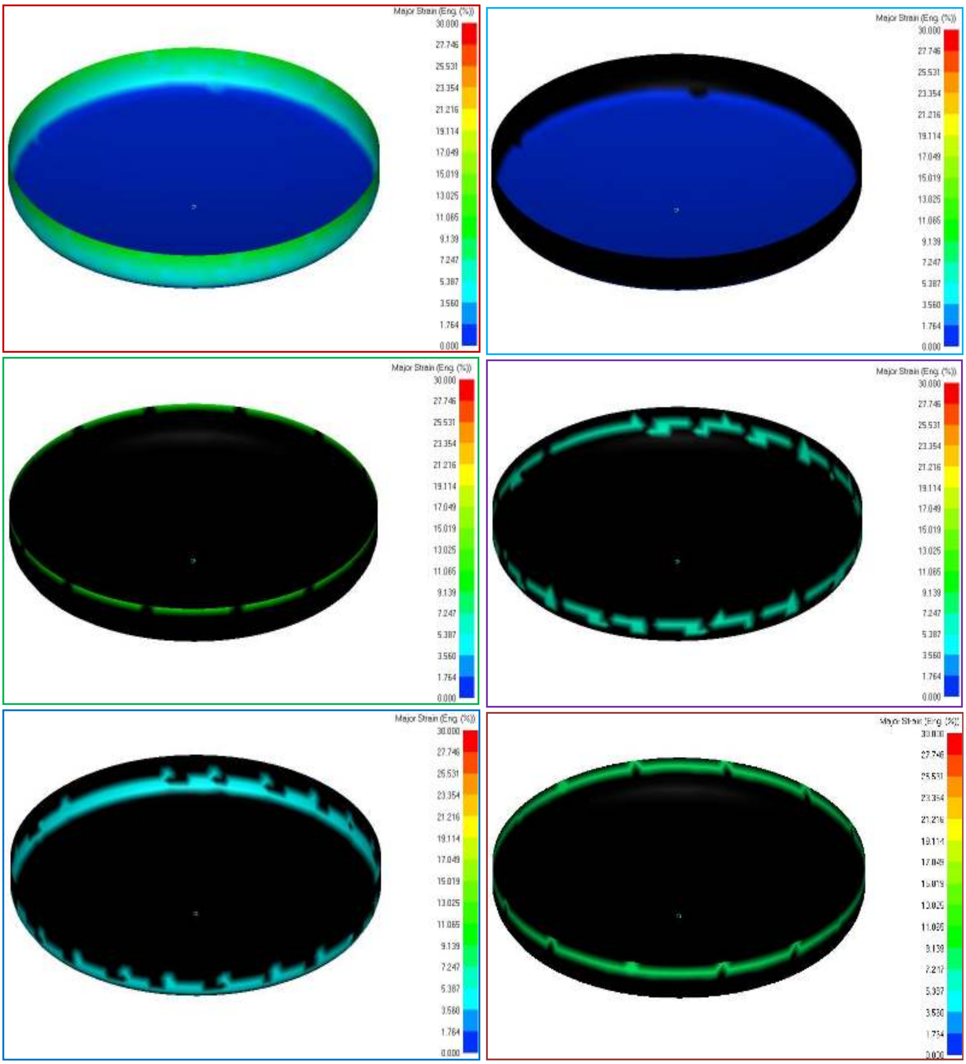


Figure 3 Petrol tank cover – major strain in nine experiments (continued) (see online version for colours)



Let’s have a close look at major strain status at various cross sections of component for experiment number one. The flat bottom has major strain in the range of 0 to 1.764%. The strain increases as we move from bottom to wall region. At the junction of bottom and wall the strain values ranges from 3.560% to 5.387%. Slightly in the upper portion of wall the strain ranges in between 5.387% to 7.247%. Above this, there is a rim where strain values can be seen from 7.247% to 9.139%. The maximum strain observed is in between 9.139% to 11.06% in the most upper region of wall, as seen in details in Figure 4.

Figure 4 Petrol tank cover – major strain distribution (see online version for colours)



5.3 *Petrol tank cover – minor strain [engineering %]*

The scale for percentage engineering minor strain plotted in experiments ranges from –14.13% to 0.586%. It is observed that maximum strain observed during nine experiments is 0.586% and minimum is 0.36%. The values of maximum strain recorded in nine experiments are presented below.

Table 6 Petrol tank cover – minor strain [engineering %]

Expt.-I	0.36%	Expt.-II	0.472%	Expt.-III	0.52%
Expt.-IV	0.371%	Expt.-V	0457%	Expt.-VI	0.570%
Expt.-VII	0.375%	Expt.-VIII	0.466%	Expt.-IX	0.586%

Figure 5 Petrol tank cover – minor strain distribution (see online version for colours)

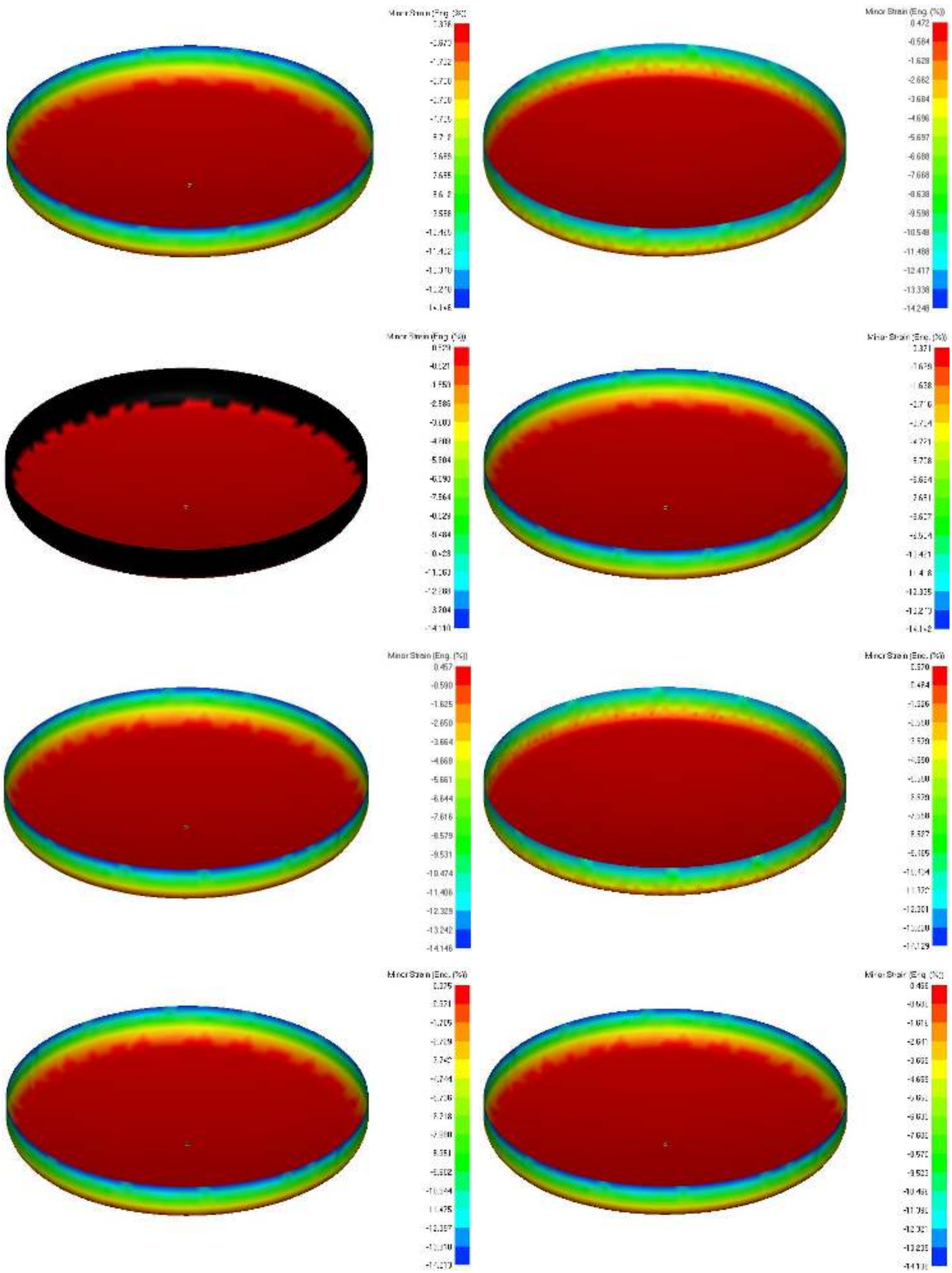
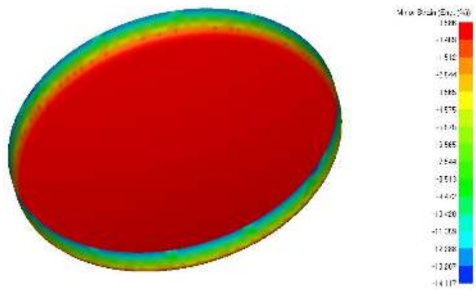


Figure 5 Petrol tank cover – minor strain distribution (continued) (see online version for colours)



6 Mathematical modelling – petrol tank cover

Linear mathematical relations have been developed from the results of Taguchi design of experiments and analysis of variance between input parameters blank holder force, friction coefficient, die profile radius and punch nose radius. The performance characteristics applied for petrol tank cover are thinning and thickening. The relationships are presented below. Minitab has been used for regression analysis. No fracture has been observed during experimentation.

$$Thinning = 0.782 + 0.000778BHF - 0.0433\mu - 0.00039R_D + 0.00069R_P \quad (1)$$

$$Thickening = 0.826 + 0.000382BHF - 0.0308\mu + 0.00219R_D + 0.000069R_P \quad (2)$$

7 Multi-objective problem formulation

Multi-objective optimisation problem has been formulated from the linear mathematical models developed. Two objectives thinning and thickening are selected. The problem formulated is as follows.

$$Minimise\ F = (F1, F2)$$

$$F1 = 0.782 + 0.000778BHF - 0.0433\mu - 0.00039RD + 0.00069R_P$$

$$F2 = 0.826 + 0.000382BHF - 0.0308\mu + 0.00219RD + 0.000069R_P$$

Subjected to:

$$1.2 \le \beta \le 2.23$$

$$RD \le RP \le 6RD$$

$$FdMax \le \pi dmS0Su$$

$$RD \ge 0.035[50 + (d0 - d1)]\sqrt{S0}$$

8 Multi-objective optimisation – genetic algorithm

MOGA is applied to achieve optimum results. Genetic algorithm mimic the principle of natural genetics (Bhoskar et al., 2015). It operates with three steps as selection, crossover and mutation. This is systematic randomised search for optimisation. It works on probabilities instead of deterministic approach. The parameters of MOGA are presented in Table 7.

Table 7 MOGAs-parameters

MOGA optimisation parameters	
Population	Double vector
Selection	Tournament
Crossover	Two point
Mutation	Constraint dependent
Migration	Foreword
Crossover probability	0.80
Pareto front fraction	0.65
Stopping criterion	Number of generations
Generations	700
Initial population	500

The Pareto front indicates various combinations of conflicting objectives. For above two objective functions thinning and thickening, the Pareto front shows various points as shown in Figure 6. The best agreement between these two objectives is selected as optimum solution.

Figure 6 Pareto front for thinning and thickening (see online version for colours)

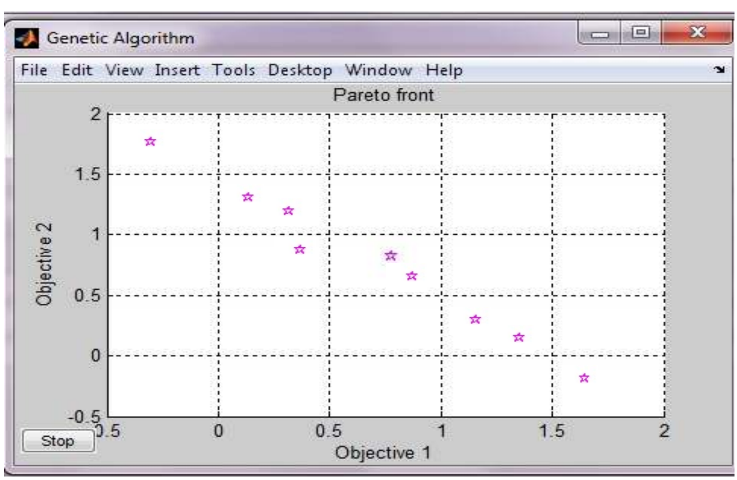


Table 8 Multi-objective optimisation results

MOGA results			
Parameter	*Lower bound*	*Upper bound*	*Optimum*
Punch dia.	59 mm	61 mm	61 mm
Friction	0.05	0.15	0.15
Thickness after thinning		0.780 mm	
Thickness after thickening		0.827 mm	

The optimisation results obtained are presented in Table 8. The optimum value of punch diameter is 61 mm and coefficient of friction of 0.15. The thinning value at these parameters is 0.780 mm and thickness after thickening is 0.827 mm.

References

Asgari, A., Pereira, M., Rolfe, B., Dingle, M. and Hodgson, P. (2005) 'Design of experiments and spring back prediction for AHSS automotive components with complex geometry', *CP778*, Vol. A, pp.215–220.

Bhoskar, T., Kulkarni, O.K., Kulkarni, N.K., Patekar, S.L., Kakandikar, G.M. and Nandedkar, V.M. (2015) 'Genetic algorithm and its applications to mechanical engineering: a Review', *Materials Today: Proceedings*, Vol. 2, Nos. 4–5, pp.2624–2630, Elsevier.

Chandra Mohan Reddy, G., Ravindra Reddy, P.V.R. and Janardhan Reddy, T.A. (2010) 'Finite element analysis of the effect of coefficient of friction on the drawability', *Tribology International*, Vol. 43, Nos. 5–6, pp.1132–1137.

Chen, F-K. and Liao, Y-C. (2002) 'An analysis of draw-wall wrinkling in a stamping die design', *International Journal of Advanced Manufacturing Technology*, Vol. 19, No. 4, pp.253–259.

Gantar, G., Kuzmana, K. and Filipi, B. (2005) 'Increasing the stability of the deep drawing process by simulation-based optimization', *Journal of Materials Processing Technology*, Vol. 165, pp.1343–1350.

Jawad, W.K. and Mohamed, J.H. (2008) 'Studying the effect of punch nose radius on deep drawing operation', *Engineering & Technology*, Vol. 26, No. 1, pp.55–73.

Kakandikar, G.M. and Nandedkar, V.M. (2013) 'Spring seat forming optimization with genetic algorithm', *International Journal of Computer Aided Engineering and Technology (IJCAET)*, Vol. 5, No. 4, pp.362–374, Inderscience Publisher.

Kakandikar, G.M. and Nandedkar, V.M. (2018) 'Spring back optimization in automotive shock absorber with genetic algorithm', *Manufacturing Reviews*, Vol. 5, No. 1, pp.1–7.

Kakandikar, G.M., Patekar, S.L., Bhoskar, T. and Kulkarni, O.K. (in press) 'Optimizing fracture in automotive tail cap by firefly algorithm, *International Journal of Swarm Intelligence*.

Wei, L. and Yuying, Y. (2008) 'Multi objective optimization of sheet metal forming process using Pareto based genetic algorithm', *Journal of Material Processing Technology*, Vol. 208, Nos. 1–3, pp.499–506.

Yagami, T., Manabe, K. and Yamauchi, Y. (2007) 'Effect of alternating blank holder motion of drawing and wrinkle elimination on deep-drivability', *Journal of Materials Processing Technology*, Vols.187–188.

Zhang, S.H., Wang, Z.R., Wang, Z.T., Xua, Y. and Chen, K.B. (2004) 'Some new features in the development of metal forming technology', *Journal of Materials Processing Technology*, Vol. 151, Nos. 1–3, pp.39–47.