Experimental Investigation and Optimization of Process Parameters on the Deep Drawing of AISI202 Stainless Steel

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Abstract

Deep drawing is one of the most important processes for forming sheet metal parts. It is widely used for mass production of cup shapes in automobile, aerospace and packaging industries. Cup drawing, besides its importance as forming process, also serves as a basic test for the sheet metal formability. The effect of equipment and tooling parameters results in complex deformation mechanism. Existence of thickness variation in the formed part may cause stress concentration and may lead to acceleration of damage. Using TAGUCHI's signal-to-noise ratio, it is determined that the punch nose radius has major influence followed by blank holder pressure and punch pressure on the thickness distribution of the deep drawn cup of Stainless Steel AISI 202 sheet. The optimum levels of the above three factors, for the most even wall thickness distribution, are found to be punch nose radius of 2 mm, punch pressure of 60bar and blank holder force of 110bar.

1. Introduction

Sheet metal forming is a significant manufacturing process for producing large variety of automotive parts and aerospace parts as well as consumer products. Deformation of sheet materials in the stamping process is classified by the four deformation modes, i.e. deep drawing, stretching, stretch flanging and bending. Deep drawing is one of the widely used sheet metalworking processes in the industries, to produce cup shaped components at a very high rate. Cup drawing, besides its importance as forming process, also serves as a basic test for the sheet metal formability. During the course of deep drawing, the following five processes take place. They are: 1) pure radial drawing between the die and blank holder, 2) bending and sliding over the die profile, 3) stretching between the die and the punch, 4) bending and sliding over the punch profile radius, and 5) stretching and sliding over the punch face. Thus, the deep drawing process involves complex deformation mechanisms. The parameters that affect the success or failure of a deep drawing operation are the punch and die radii, the punch and die clearance, the press speed, the lubrication and the type and the extent of restraint to metal flow material in deep-drawn shapes. Among these, the punch force [1, 12], punch nose radius [1, 2, 6, and 7] and the blank holder force [2, 3, 5, and 11] are considered to be the significant parameters in deep-drawing processes. There are two classifications of drawing, deep drawing and shallow drawing. With deep-drawing, the drawn cup is deeper than one-half its diameter, whereas in shallow drawing it is less than one-half its diameter. Thinning of the walls tends to be more of a problem with deep-drawing as opposed to shallow drawing [5, 14, 22]. Wrinkling occurs at the edges. In the field of deep-drawing much experimental and research work has been published. The results were claimed to be sufficiently accurate to provide a basis of reference for theoretical treatments of cup-drawing [1, 2, 7], as well as an empirical basis of comparison between different drawing conditions. Thickness is one of the major quality characteristics in sheet metal formed part. The thickness is unevenly distributed in the part after deep drawing [7, 17, 21]. Generally, the thickness is uniform at the bottom face of the punch, minimum at the punch nose radius and vertical surface, and thicker at the flange area. Existence of thickness variation from the production stage may cause stress concentration in the part, leading to the acceleration of damage. The selection of appropriate process parameters and their combination results in high quality parts. In this work, a statistical approach based on TAGUCHI's signal-to-noise ratio [2, 18] was adopted to determine the degree of importance of the parameters such as die shoulder radius, punch nose radius and the blank holder force on the thickness distribution of the deep drawn cup of stainless steel sheet AISI202 and to determine the optimum combination of these three factors for the most even wall thickness distribution.

2. Materials and equipment details

The material used in the present work was the commercially available stainless steel AISI202.The main composition of this particular grade of SS is 18% Chromium and 8% Nickel. The chromium and nickel gives it the corrosion resistance that such components generally require. The thickness of the sheet was 0.80 mm. The results of tensile test performed on blank material are provided in table 1.

Table.1 Uniaxial tensile test data

Proof Stress	Tensile Strength	Elongation
310MPa	655MPa	40%

Table.2 Equipment details

Type of Press	Closed frame
Application	Deep Drawing Press
Capacity	125 T
Stroke	800 mm
Daylight	700 mm
Table Size	750 X 750 mm
Power	20 HP X 3 PH X 1440 RPM

3. Parameters and levels

3.1. Selection of Parameters

In sheet metal forming, a thin blank sheet is subjected to plastic deformation using forming tools to conform to a designed shape. During this process, the blank sheet is likely to develop defects if the process parameters are not selected properly. Therefore, it is important to optimize the process parameters to avoid defects in the parts and to minimize production cost. Optimization of the process parameters such as die radius, blank holder force, punch nose radius, etc., can be accomplished based on their degree of importance on the sheet metal forming characteristics. There are various defects associated with a deep drawing process like thinning of walls, cracking [4, 19, 20] etc. The process parameters should be properly combined so that we get an optimum process by which we get minimum defects. Optimization of process parameters in sheet metal forming is an important task to reduce manufacturing cost. To determine the optimum values of the process parameters, it is essential to find their influence on the deformation behaviour of the sheet metal. Further analysis on the defects allows for selecting the most important contributing factors.
Out of all these defects that normally occur during sheet metal forming, there are a few defects that are specifically faced during deep drawing of various components which in our case is a cylindrical component. The problems that are particularly based on tooling effects are discussed and optimised during our work. Defects that are common to see during deep drawing of cylindrical components are tearing, wrinkling, compression marks and uneven distribution of material. All these defects can then lead to smaller but prominent problems of thickness variation in parts. Thickness is one of the major quality characteristics in sheet metal formed part. The thickness is unevenly distributed in the part after deep drawing [9, 12]. Generally, the thickness is uniform at the bottom face of the punch, minimum at the punch nose radius and vertical surface, and thicker at the flange area. Existence of thickness variation from the production stage may cause stress concentration in the part, leading to the acceleration of damage [16, 20]. Thus this problem is effectively reduced by performing an optimisation process on the parameters that can most affect the variation in thickness. The selection of appropriate process parameters and their combination results in high quality parts. Based on the cause and effect diagram shown below, we recognise the signal factors that can be optimised and work on them. Further analysis is done on the changes that occur in deep drawing by three particular parameters namely [2, 6, 15]:

- Punch Nose Radius (PNR).
- Punch Pressure (PP).
- Blank Holder Pressure (BHP).

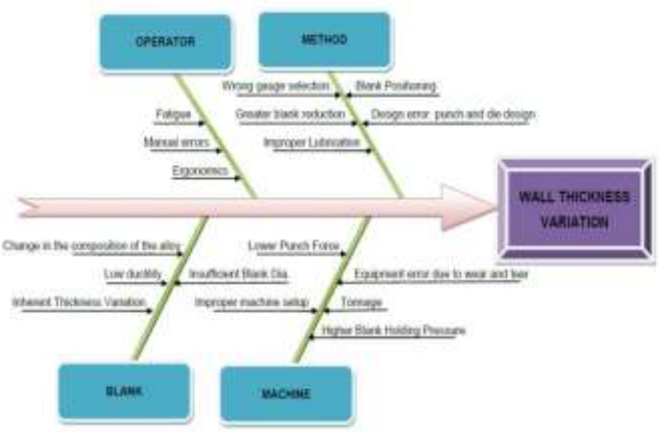

Fig.1 Cause and effect diagram.

3.2. Trials to determine levels using design of experiments

The effect of many different parameters on the performance characteristic in a condensed set of experiments can be examined by using the orthogonal array experimental design proposed by Taguchi. Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter [8, 10, 13]. If the difference between the minimum and maximum value of a parameter is large, the values being tested can be further apart or more values can be tested. If the range of a parameter is small, then less value can be tested or the values tested can be closer together. Typically, the number of levels for all parameters in the experimental design is chosen to be the same to aid in the selection of the proper orthogonal array. Knowing the number of parameters and the number of levels, the proper orthogonal array can be selected. Using the array selector table shown below, the name of the appropriate array can be found by looking at the column and row corresponding to the number of parameters and number of levels. Once the name has been determined (the subscript represents the number of experiments that must be completed), the predefined array can be looked up. Links are provided to many of the predefined arrays given in the array selector table. These arrays were created using an algorithm Taguchi developed, and allows for each variable and setting to be tested equally.

Table.3 Experimental details

Exp. No	PNR (mm)	PP (bar)	BHP (bar)
1	2	50	110
2	2	50	120
3	2	50	130
4	2	55	110
5	2	55	120
6	2	55	130
7	2	60	110
8	2	60	120
9	2	60	130
10	5	50	110
11	5	50	120
12	5	50	130
13	5	55	110
14	5	55	120
15	5	55	130
16	5	60	110
17	5	60	120
18	5	60	130
19	8	50	110
20	8	50	120
21	8	50	130
22	8	55	110
23	8	55	120
24	8	55	130
25	8	60	110
26	8	60	120
27	8	60	130

3.3. Experimental details

The deep drawing was conducted using a deep drawing hydraulic press with a maximum load capacity of 125tonnes. The lubricant used was soap water. The experimental setup is shown in Fig 2. The blanks of 259 mm in diameter were cut from the sheet and cups were drawn according to the experimental design. Drawn cups were sectioned at the middle and are shown in Fig 3 The details of the equipment used to conduct experimental trials are shown in table 2.

Fig.2 Photograph of experimental setup.

The drawn cups were sectioned at the middle and the thickness was measured at ten points at uniform intervals from the centre of the cup to the edge of the flange, as shown in Fig 4. The measured thickness values are shown in Table 4

Fig.3 Cups sectioned at middle.

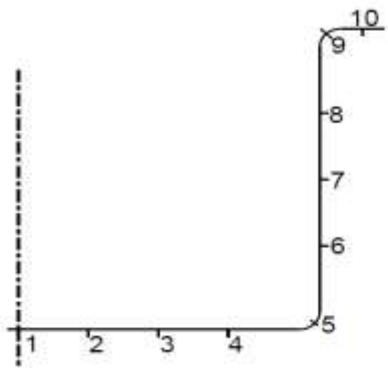

Fig.4 Points of thickness measurements

3.4. Signal to Noise ratio

One of the quality criteria in sheet metal formed parts is thickness distribution. Failure in deep drawn parts usually occurs by thinning; therefore, it is important to determine the variation of strain in thickness direction during deformation. The objective is to reduce thickness variation in deep drawn part. Therefore, in this study, the response selected from the experiments is the thickness distribution.

Table.4 Measured thickness values of cups (mm).

Trial	1	2	3	4	5	6	7	8	9	10
1	0.39	0.4	0.39	0.39	0.37	0.4	0.38	0.39	0.46	0.47
2	0.39	0.4	0.39	0.39	0.36	0.38	0.38	0.39	0.45	0.48
3	0.39	0.39	0.39	0.38	0.36	0.4	0.4	0.4	0.46	0.47
4	0.39	0.38	0.38	0.37	0.36	0.4	0.41	0.41	0.45	0.46
5	0.38	0.38	0.38	0.37	0.35	0.38	0.4	0.41	0.45	0.46
6	0.37	0.38	0.37	0.37	0.35	0.38	0.41	0.4	0.45	0.47
7	0.38	0.38	0.38	0.38	0.36	0.4	0.4	0.41	0.44	0.46
8	0.38	0.38	0.38	0.38	0.36	0.41	0.4	0.4	0.45	0.46
9	0.38	0.38	0.37	0.37	0.36	0.4	0.41	0.41	0.46	0.46
10	0.37	0.38	0.39	0.38	0.35	0.43	0.41	0.42	0.46	0.46
11	0.38	0.38	0.38	0.39	0.35	0.42	0.42	0.41	0.45	0.46
12	0.39	0.39	0.38	0.39	0.36	0.38	0.41	0.43	0.46	0.47
13	0.38	0.38	0.38	0.39	0.35	0.39	0.4	0.39	0.44	0.46
14	0.38	0.39	0.39	0.39	0.37	0.41	0.4	0.39	0.47	0.48
15	0.38	0.38	0.37	0.39	0.34	0.41	0.42	0.42	0.45	0.46
16	0.39	0.39	0.39	0.38	0.37	0.42	0.42	0.41	0.46	0.47
17	0.37	0.37	0.38	0.37	0.36	0.41	0.41	0.42	0.45	0.46
18	0.38	0.38	0.38	0.38	0.36	0.4	0.4	0.4	0.46	0.48
19	0.39	0.38	0.37	0.37	0.36	0.4	0.4	0.4	0.46	0.47
20	0.38	0.38	0.38	0.37	0.35	0.4	0.41	0.41	0.46	0.47
21	0.37	0.37	0.37	0.37	0.36	0.41	0.4	0.41	0.46	0.47
22	0.37	0.37	0.36	0.37	0.35	0.37	0.38	0.39	0.44	0.46
23	0.38	0.38	0.37	0.38	0.35	0.39	0.4	0.41	0.46	0.47
24	0.37	0.37	0.38	0.37	0.36	0.39	0.42	0.4	0.46	0.47
25	0.39	0.38	0.38	0.38	0.35	0.41	0.41	0.41	0.46	0.47
26	0.37	0.39	0.39	0.38	0.35	0.42	0.41	0.4	0.45	0.46
27	0.38	0.37	0.37	0.38	0.35	0.41	0.42	0.41	0.45	0.46

The response of a system, and, as a result, its quality characteristics, are influenced by three types of factors: 1) signal factors that are set by the operator of the system in later stages of the product life; 2) control factors that are set by the designer of the system; and 3) noise factors that cannot be directly controlled by neither the designer nor the operator. Control factors are those design parameters that can be freely specified by the designer. TAGUCHI divided these control factors into two subsets, with one subset consisting of those factors influencing both the response mean and the response variance, and second subset consisting of those factors influencing only the response mean[9]. Noise factors are usually classified by TAGUCHI into three classes: 1) external noise factors that typically describe the environmental conditions, such as temperature, dust and humidity; 2) unit-to-unit variation that typically addresses the inevitable variations in a manufacturing process; and 3) deterioration that typically refers to the deterioration in functional characteristics of sold products as time passes. TAGUCHI's main idea was to control the noise factors indirectly by examining how they are affected by different settings of the control factors. He suggested analyzing the joint effects of control and noise factors, and for this purpose, proposed a performance criterion called signal-to-noise ratio (*S*/*N*).Defects such as wrinkles and excessive localized thinning alter the product geometry from the designed one, causing difficulties in joining and assembly of sheet products, and limiting the product serviceability. Therefore, thickness of the deep drawn cup section should be as uniform as possible, i.e. the nominal values are preferred throughout the section. If the nominal value for a characteristic is the best, then the designer should maximize the *S*/*N* ratio, accordingly the *S*/*N* ratio chosen is given in equation 1.

$$\eta = 10 \ln_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{\mu^2}{\sigma^2} \quad \text{------ (1)}$$

where η = S/N ratio, y_i= value of the quality characteristic at i^{th} setting, n = Total number of trials at the i^{th} setting, μ= Mean and σ = standard deviation. The calculated *S*/*N* ratios for experiments are shown in Table 5 and the mean responses are shown in Table 6. Although the physical meaning of *S*/*N* ratio is not as straight forward as simple level average response analysis by values, it is more objective towards the target because the *S*/*N* ratio reflects both the average (mean) and the scatter (variance) [23]. For optimum values of the selected parameters, the level that gives the highest *S/N* ratio was chosen [24].

Table.5 *S/N* ratio for experiments.

Trial. No	S/N Ratio	Trial.No	S/N Ratio
1	21.653	14	20.727
2	20.927	15	20.707
3	21.401	16	21.798
4	21.742	17	21.015
5	21.067	18	20.434
6	20.252	19	20.649
7	22.273	20	20.370
8	21.852	21	20.135
9	20.939	22	20.690
10	20.671	23	20.327
11	21.401	24	20.198
12	20.979	25	20.722
13	21.935	26	21.390
		27	20.865

4. Regression Analysis

Regression analysis is the statistical technique that identifies the relationship between two or more quantitative variables: a dependent variable, whose value is to be predicted, and an independent or explanatory variable (or variables), about which knowledge is available. The technique is used to find the equation that represents the relationship between the variables. A simple regression analysis can show that the relation between an independent variable X and a dependent variable Y is linear, using the simple linear regression equation Y= a + bX (where a and b are constants). Multiple regressions will provide an equation that predicts one variable from two or more independent variables [2, 9],

$$Y=a+bX_1+cX_2+dX_{3+....}$$

Regression analysis is used to understand the statistical dependence of one variable on other variables. The technique can show what proportion of variance between variables is due to the dependent variable, and what proportion is due to the independent variables. The relation between the variables can be illustrated graphically, or more usually using an equation. This statistical technique is most commonly used in program evaluation to estimate effects. The net effects of the program under evaluation can be assessed using regression analysis, by attributing part of the changes observed to explanatory variables, while the remaining effects are attributed to the program. For this reason, regression analysis is useful in ex-post evaluation, to determine the net impact of the program.

The regression equation for the standard deviation values of the experiment was derived using MINITAB. The equation was:

STDE1 = 0.0244148 + 0.000492444 PR - 0.00014514 PF + 0.000140698 BHF

R^2 value obtained for this model was .834 which shows that predicted model is valid. This equation is then used to predict the standard deviation values and they are compared with the actual values.

5. Results and Discussions

The response table for signal to noise ratio and standard deviations as shown in table 7 and 8 indicates the order of importance of the three parameters and they are in the order of Punch Nose Radius, Blank Holding Force and then the Punch Force.

Table.7 Response table for Signal to Noise ratio.

Level	PR	PF	BHF
1	21.35	20.91	21.35
2	21.07	20.85	21.01
3	20.59	21.25	20.66
Delta	0.75	0.40	0.69
Rank	1	3	2

Table.8 Response Table for Standard Deviations.

Level	PR	PF	BHF
1	0.03433	0.03631	0.03438
2	0.03572	0.03616	0.03577
3	0.03728	0.03486	0.03719
Delta	0.00295	0.00145	0.00281
Rank	1	3	2

5.1 Effect of punch nose radius

Effect of Punch nose radius on the S/N ratio and standard deviation of the thickness is shown in fig. 5 and 6.

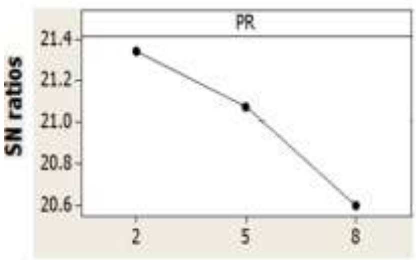

Fig.5 Effect of Punch nose radius on the S/N ratios.

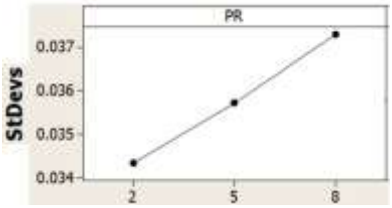

Fig.6 Effect of Punch nose radius on the Standard deviation of thickness

This graph shows that the S/N ratio decrease and the standard deviation increase with increase in the punch nose radius thus suggesting a lower punch nose radius for lesser thickness variation and also better results from the drawing operation.

5.2 Effect of punch force

Effect of Punch force on the S/N ratio and standard deviation of thickness is shown in fig. 7 and 8.

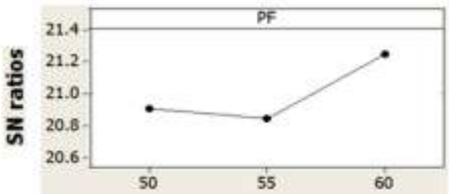

Fig.7 Effect of Punch force on the S/N ratios

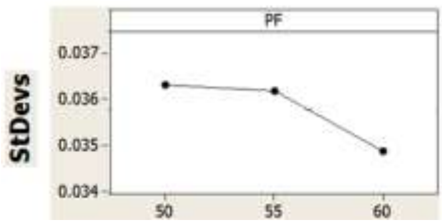

Fig.8 Effect of Punch force on the Standard deviation of thickness.

The S/N ratio graph shows that the S/N ratio first decreases and then increases suggesting that the point for higher S/N ratio gives the best results. Also the standard deviation decreases with the increase in punch force. Both these graphs indicate that a higher punch force is required to produce optimum results during drawing.

5.3 Effect of blank holder force

Effect of Blank holder force on the S/N ratios and standard deviation of thickness is shown in fig 9 and 10.

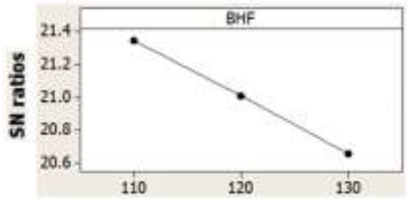

Fig.9 Effect of Blank holder force on the S/N ratios

Effect of Blank holder force on the Standard deviation of thickness is given below:

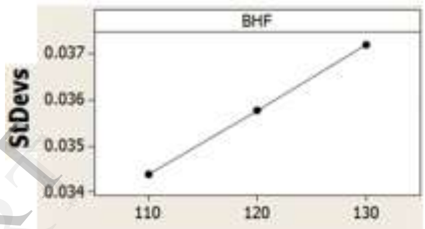

Fig.10 Effect of Blank holder force on the Standard deviation of thickness

The plots for Blank holding force versus S/N ratios and standard deviation show almost a linear relationship for both the variables. This indicates that for a higher S/N ratio and a lower standard deviation plot, a lower blank holding force gives the optimum results. Thus a lower blank holding force ensures uniform thickness by not applying excessive pressure on the flange. The measured and predicted values based on the regression equation for the standard deviation are shown below along with the error percentage.

Table.9 Comparison of standard deviation values.

Trial No.	PR	PF	BHF	Actual Std. Dev.	Predicted Std. Dev.	Error (%)
1	2	50	110	0.03339	0.03368	-0.84
2	2	50	120	0.03604	0.03472	3.6525
3	2	50	130	0.03438	0.03541	-3.012
4	2	55	110	0.03281	0.03200	2.4601
5	2	55	120	0.03502	0.03634	-3.766
6	2	55	130	0.03836	0.03785	1.3338
7	2	60	110	0.03071	0.03124	-1.715
8	2	60	120	0.03231	0.03231	0.0081
9	2	60	130	0.03590	0.03537	1.4596
10	5	50	110	0.03749	0.03559	5.0632
11	5	50	120	0.03438	0.03611	-5.031
12	5	50	130	0.03627	0.03643	-0.464
13	5	55	110	0.03169	0.03246	-2.449
14	5	55	120	0.03743	0.03628	3.0648
15	5	55	130	0.03705	0.03742	-1.001
16	5	60	110	0.03333	0.03445	-3.366
17	5	60	120	0.03559	0.03500	1.637
18	5	60	130	0.03823	0.03769	1.4104
19	8	50	110	0.03711	0.03873	-4.358
20	8	50	120	0.03842	0.03801	1.0759
21	8	50	130	0.03928	0.03808	3.0653
22	8	55	110	0.03565	0.03568	-0.087
23	8	55	120	0.03842	0.03825	0.447
24	8	55	130	0.03900	0.03914	-0.361
25	8	60	110	0.03717	0.03552	4.4343
26	8	60	120	0.03425	0.03483	-1.709
27	8	60	130	0.03620	0.03727	-2.937

The table above shows that there is minimal error between the actual and predicted values for the standard deviation values suggesting that the regression model that was developed was satisfactory. The plot indicating the comparison of the actual and predicted values of standard deviation for the various experiments is shown in fig.11

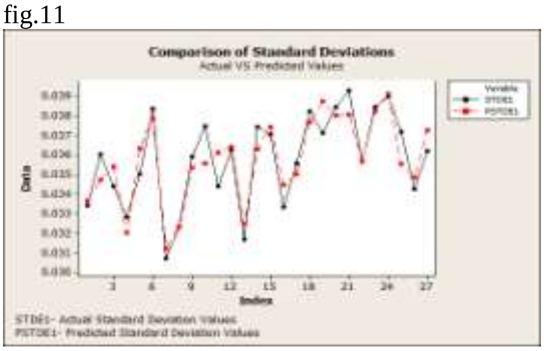

Fig.11 Comparison of standard deviations

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