# Effect of Forming Conditions on Localized Thinning in Deep Drawing Process

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***Abstract***— **The present work aims to investigate and optimize the localized thinning of aluminum 7075 sheet metal during deep drawing process. A parametric axi-symmetric model was developed to allow conducting a set of automated simulations by varying some sensitive's geometry and process parameters. Three significant process parameters, namely blankholder clearance, friction coefficient and punch radius, were investigated. The main observed defect is the localized thinning of the sheet during punching process. This defect can be avoided by determining the optimal parameters. Taguchi Design of Experiment (DE) method combined with finite elements model form a refined predictive tool to determine thinning and the most sensitive parameter. A python script (in ABAQUS) was developed to automatize simulations of deep drawing process according to the experimental configurations. The results show that the lowest blankholder clearance, required to eliminate sheet metal localized thinning, is found to be equal or less than 0.01 mm. In addition, the lowest punch radius values have better deep drawing performance when the gap between die and punch does not exceed 1.28 mm. The most dominant parameters, affecting on the localized thinning defect, are punch radius as well as the friction coefficient. Blankholder clearance is also considered as an important parameter affecting on the forming quality and especially on the position where sheet metal thinning occurs.**

***Keywords— Localized Thinning; Deep Drawing; Design Of Experiments; Finite Element***

## I. INTRODUCTION

Sheet metal stamping process is one of the most important manufacturing processes in the automotive industries. In the last years, the international competition of the industries is extremely severe; most of researches try to reduce the manufacturing costs and to increase productivity, strength and quality of the forming as well. Several studies have been applied towards the development of new materials and new technologies to be used for successive bending, unbending, re-bending, extension, and shearing. Regarding to another study of Abdullah et al. [1], a new technique of deep drawing process was proposed for producing elliptic cups; the effects of blank thickness and clearance ratio were numerically and experimentally investigated on limiting drawing ratio and punch load. It was conclude that the proposed technique appears to be convenient for deep drawing of brass sheets of thicknesses values of 1.9 to 3 mm. Regarding to the deep drawing process, it's necessary to use several procedures in order to obtain a piece of complex shape or/and a piece of simple shape due to sheet metal formability limits, or restrains imposed. Harada et al. 2014 [2] have investigate the effect of the coating condition on the formability of Titanium alloys during the multistage deep drawing processes; it was noted that deep drawing of extremely long cups became possible with more than 6 passes.

Otherwise, a good formability (or product quality) is related to proper part characteristics: without localized thinning, without wrinkling in the flange or on the wall of the part, without fracture of the workpiece and without geometrical defects due to springback, etc. All these defects depend mainly on the selected parameters: geometric, material, process, etc. In addition, optimization based only on experimental approaches often requires long and expensive trials. So, numerical simulations and mathematical methods of optimization [3-8] are increasingly used to evaluate the forming difficulties in sheet metal forming, and to achieve these goals.

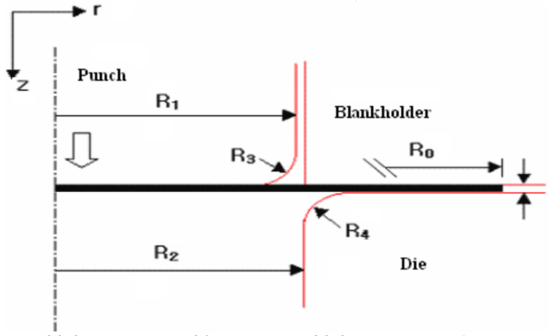
The Taguchi method [9] allows to optimize processes from a reliability viewpoint and product costs. In a domain such as stamping, this method can be of a great help in terms of reliability and product cost. This method was often used, when it's important to evaluate the influence of parameters on an observed defect or any selected output [10-13].

Several studies have been devoted to the prediction and optimization of springback problem [14, 15], wrinkling [16, 17], and localized thinning [18]. However, there are few studies that provide details on the number and position of thinning. Thus, this study focuses on a parametric simulation of sheet metal forming in order to predict and minimize the localized thinning. This is strongly related to process parameters and tools geometry such as: i- punch and die radius, ii- gap between punch and die, iii- blankholder force (or die/blankholder clearance), iv- friction coefficient. Suitable number of independent simulations must be conducted based on some observed extreme conditions to preselect design parameters.

In this work, the DoE method was applied to study the effects and interaction of some stamping parameters on thinning. The aim of this study is to find the optimal combination providing the best response. A FE model based on a combined nonlinear isotropic/kinematic hardening law was used to study the deep drawing process. This study proposes a parametric simulation of sheet metal forming process in order to predict and minimize the localized thinning.

## II. Application and Finite Element Model of Cylindrical Cup

The geometry of the selected benchmark test is shown in Fig. 1. The material, process and tool-workpiece parameters are listed in Table 1.




$R_0$ = 22.25 mm ; $R_1$ = 20 mm ; $R_2$ = 22.25 mm ; $R_3$ = 1 mm ; $R_4$ = 5 mm

Fig. 1. Geometry parameters of the model.

A combined nonlinear isotropic/kinematic hardening law is introduced in the finite element model with optional parameters to specify the calibrated kinematic hardening material parameters and the number of backstresses. The hardening behavior of the model defines the evolution of the yield surface size, $\bar{\sigma}$, as a function of the equivalent plastic strain, $\bar{\varepsilon}^{pl}$, using the simple exponential law:

$$\bar{\sigma} = \bar{\sigma}_0 + Q_\infty \left(1 - e^{-b\,\bar{\varepsilon}^{pl}}\right) \quad (1)$$

Where $\bar{\sigma}_0$ is the yield stress at zero plastic strain and $Q_\infty$ and $b$ are calibrated kinematic hardening material parameters.

When the equivalent stress defining the size of the yield surface remains constant ($\bar{\sigma} = \bar{\sigma}_0$), the model reduces to a nonlinear kinematic hardening model. This model account for the following phenomena: Bauschinger effect, Cyclic hardening with plastic shakedown, Ratchetting, Relaxation of the mean stress.

Due to the symmetry, the numerical simulations of the deep-drawing process were performed by using a half of 2D axisymmetric numerical model in order to reduce the computational time. Four-node axisymmetric elements and two degrees of freedom per node (CAX4R) and Gaussian reduced-integration points through thickness direction were used to mesh the blank sheet metal. These elements are suitable to evaluate more precisely thickness diminution along the formed sheet. Punch, die and blankholder were modeled by rigid body; three references nodes were used to govern the motion and apply boundary condition of these tools.

Table 1. Description of numerical parameters used of aluminium 7075 [19].

| | | |
|---|---|---|
| Initial thickness | 1 mm | |
| Young's modulus | 73 GPa | |
| Poisson's ratio ν | 0.33 | |
| Density | 2810 kg/m³ | |
| Friction coefficient (μ) | 0-0.2 | |
| Punch radius (PR) | 0.5-3 mm | |
| Punch displacement | 10-20 mm | |
| Blankholder clearance (BH) | 0.01-0.05 mm | |
| Kinematic hardening | parameter C | 0 |
| | parameter $\gamma$ | 1 |
| | Yield stress $\bar{\sigma}_0$ | 130 MPa |
| Isotropic hardening | Equivalent Stress at zero plastic strain $\bar{\sigma}$ | 130 MPa |
| | parameter $Q_\infty$ | 280 |
| | parameter $b$ | 10 |

## III. Numerical Implementation and Preliminary Results

In order to control the selected design parameters their geometrical dependences must be determined. The variation of the punch and die diameters directly affects the gap between them. While changes on punch and die radius affects the state of contact between the sheet and these tools. Moreover variation of the gap between die and blankholder (BH) allows controlling sliding of the blank through them. An optimal choice of this parameter ensures a smooth sliding and a better forming quality of the sheet.

The computer implementation of the numerical approach is based mainly on the Taguchi method using Matlab and Abaqus software's as shown in Fig. 2. Two main interactive tools characterize the implemented approach. The first tool is a generic Python script coupled with Abaqus input file to run several finite element simulations. Combinations of input parameters are transmitted to each Abaqus simulation according to established DoE. Then, at the end of each simulation, two outputs are extracted and saved into local database. The second tool is a Matlab program which allows analyzing this database.

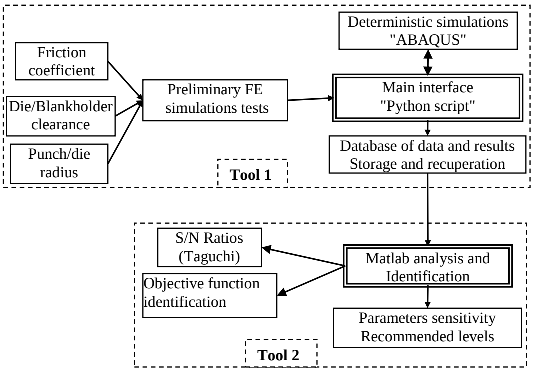



Fig. 2. Flowchart of the implemented approach.

Fig. 3 shows some tests to analyze the limits of localized thinning. The idea is based on the forming of the axi-symmetric model by varying its parameters such that punch radius, die/blankholder clearance and forming depth. Two series of punch radius are selected 1 mm (Fig. 3 a-c) and 3 mm (Fig. 3 d-g). Subsequently, three significant values (0.05, 0.2 and 0.5 mm) of die/blankholder clearance have been tested. The friction coefficient is fixed at 0.2.

The position of localized thinning depends strongly on die/blankholder clearance and punch radius. Very high values of these parameters cause a thinning at the top of the sheet metal. For example, for a punch radius equal to 3 mm and a blankholder clearance equal to 0.5 mm (Fig. 3-f) the localized thinning occurs at the top of the sheet metal. When these parameters decrease, the thinning moves to the bottom (Fig. 3-g) following a multivariable complex function. Thickness of the formed sheet was measured at all the nodes along its length and the minimum was extracted for comparison.

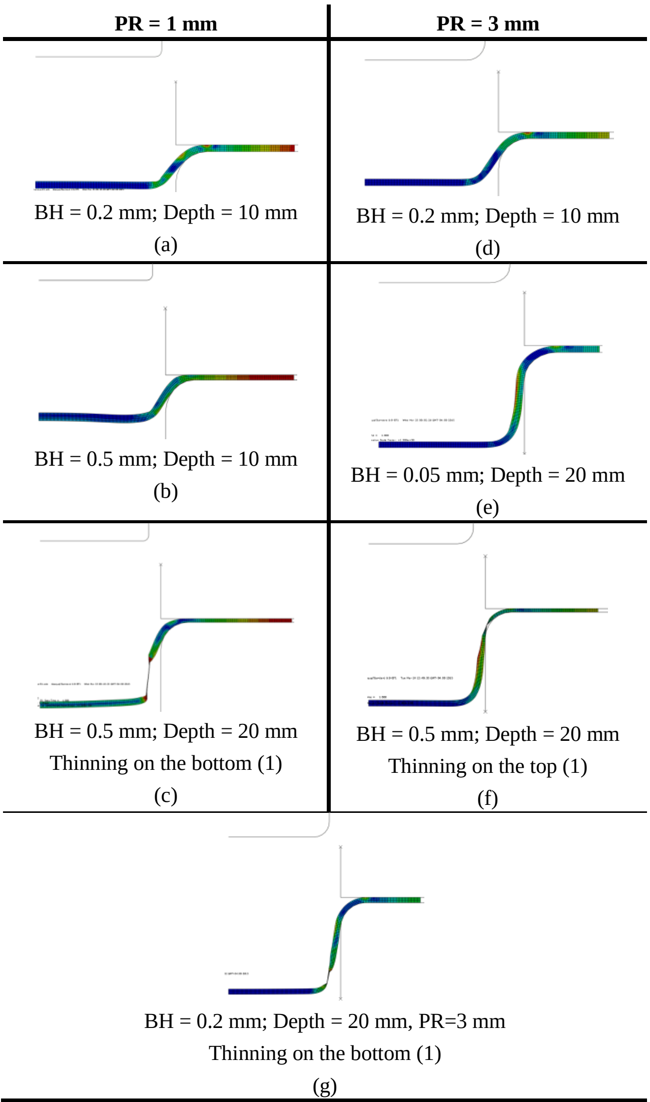



Fig. 3. Number and position of localized thinning, μ=0.2.

## IV. TAGUCHI METHOD EFFECT OF FORMING PARAMETERS ON LOCALIZED THINNING

Design of experiments [20-23] is a powerful tool to provide information such as the effects and/or interaction between factors and sheet behaviour in forming process. This method allows to find the best combination of preselected factors with a minimum number of analyses. The orthogonal arrays (OA), forms the basis for the experimental/numerical analysis in the Taguchi method. After conducting the analyses according to an OA, and to determine the effect of each factor has on the response, the signal to noise (S/N) ratio is calculated for each analysis conducted. There are three categories of S/N ratios depending on the type of demanded characteristics:

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Higher is better (HB) : $\frac{S}{N} = -10\log(\frac{1}{n}\sum\frac{1}{y^2})$

Nominal is best (NB) : $\frac{S}{N} = -10\log(\frac{1}{n}\sum\frac{\bar{y}^2}{\sigma^2})$

Lower is better (LB) : $\frac{S}{N} = -10\log(\frac{1}{n}\sum y^2)$

where n is the number of observations, y the observed data, $\bar{y}$ the average observed data, and σ the variance of $y$.

For all categories, the optimum level is the one which gives the highest value of S/N ratio. The "Lower is better" (LB) characteristic is used to reach the lowest punch force and the "Higher is better" (HB) is applied to maximize the thinning values.

In this study, three independent parameters (Friction coefficient, Die-blankholder clearance, and Punch radius) were selected and a standard (OA) $L_{27}(3^{13})$ was employed. The OA $L_{27}(3^{13})$ is used due to its capability to check the interactions among the factors and it makes use of three levels for each. Taguchi's table is associated to one or more linear graphs ready to be used [24]. The selected factors could be partitioned into four groups according to the difficulty encountered to update the FE model when changing factor level, from easiest to difficult to change:

Group 1: symbol ○ if levels are difficult to change.
Group 2: symbol ◎ if levels are less difficult to change.
Group 3: symbol ◉ if levels are enough easy to change.
Group 4: symbol ● if levels are easy to change.

In this numerical study, it can be considered that the three factors subjected to the analysis are easy to change. Therefore, all factors are taken as being easy to change. As shown in Fig. 4, a linear graph is used to assign the factors and interactions to various columns of the orthogonal array. Table 2, indicates the factors and levels in forming test. Factors A, B and C are arranged in columns 1, 2 and 5, respectively, in the standard $L_{27}$ $(3^{13})$ orthogonal array as shown in Table 3.

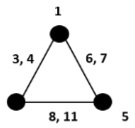



Fig. 4. Linear graph for $L_{27}$ array.

Table 2. Levels of the variables used in the experiment.

| Control factor | Level | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A : μ | 0 | 0.1 | 0.2 |
| B : BH [mm] | 0.01 | 0.03 | 0.05 |
| C : PR [mm] | 0.5 | 1.75 | 3 |

The plan of the experiments is as follows: the first column is assigned to friction coefficient (A), the second column to die-blankholder clearance (B) and the fifth column to punch radius (C), the third and fourth columns are assigned to $(A\times B)_1$ and $(A\times B)_2$, respectively, to estimate interaction between friction coefficient (A) and die-blankholder clearance (B). The sixth and seventh columns are assigned to $(A\times C)_1$ and $(A\times C)_2$, respectively, to estimate interaction between friction coefficient (A) and punch radius (C). The ninth and 11th columns are assigned to $(B\times C)_1$ and $(B\times C)_2$, respectively, to estimate interaction between die-blankholder clearance (B) and punch radius (C).

**Table 3. Orthogonal array for $L_{27}$ ($3^{13}$) Taguchi design.**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *A* | *B* | $(A\ x\ B)_1$ | $(A\ x\ B)_2$ | *C* | $(A\ x\ C)_1$ | $(A\ x\ C)_2$ | $(B\ x\ C)_1$ | - | - | $(B\ x\ C)_2$ | - | - |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 2 | 2 | 2 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 3 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 2 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 2 | 3 | 1 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 3 | 1 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 1 | 2 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 1 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 3 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 3 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 | 1 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 |

## V. RESULTS AND DISCUSSION

The numerical results carried out, regarding to the Taguchi OA of 27 combinations are reported in Table 4.

The arithmetic mean of all responses, $y_i$, concerning thinning and punch force, are estimated as follow:

$$m = \frac{\sum_{i=1}^{27} y_i}{27} \tag{2}$$

where $i$ is the experiment number.

The effect of a given factor, $A$, at level, $k$, on the response is calculated by the following formula:

$$a_k = \overline{y(A_k)} - m \tag{3}$$

where $\overline{y(A_k)}$ the arithmetic mean evaluation of factor $A$, when its level is fixed at "$k$" :

$$\overline{y(A_k)} = \frac{\sum_{1\le i\le r(A_k)} y_i(A_k)}{r(A_k)} \tag{4}$$

where $r(A_k)$ is the number of evaluations associated to $A$ at its level $k$.

On the other hand, the estimation of interaction terms of factors, $A$ and $B$, is done as follows:

$$(ab)_{kl} = \overline{y(A_k;B_l)} - m - a_k - b_l \tag{5}$$

where $\overline{y(A_k;B_l)}$ the arithmetic mean of factors, $A$ and $B$, on the response when their levels are fixed at $k$ and $l$, respectively:

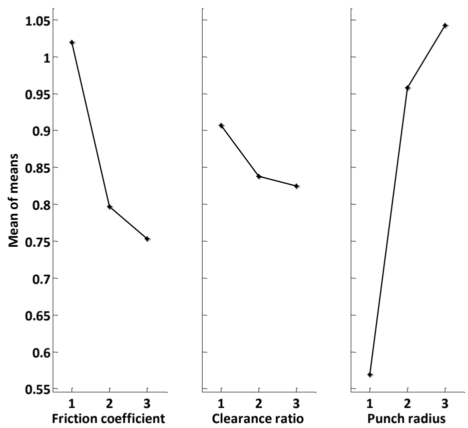
$$\overline{y(A_k;B_l)} = \frac{\sum_{1\le i\le r(A_k;B_l)} y_i(A_k;B_l)}{r(A_k;B_l)} \tag{6}$$

where $r(A_k;B_l)$ is the number of evaluations associated with the parameters $A$ and $B$ at their levels $k$ and $l$, respectively.

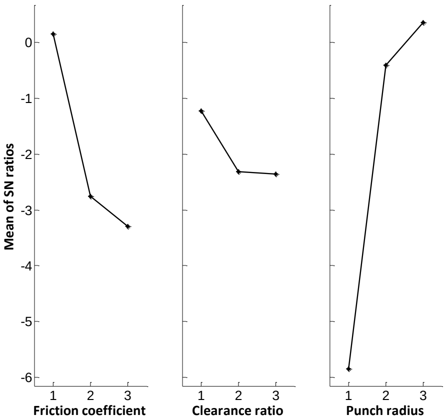
Table 4. Orthogonal array $L_{27}$ of the modeling runs and results.

| Trial | μ | BH | PR | Thickness | S/N (HT) | Punch force | S/N (LB) |
|---|---|---|---|---|---|---|---|
| | A | B(mm) | C(mm) | (mm) | (dB) | (N) | (dB) |
| 1 | 0 | 0.01 | 0.5 | 0.947 | -0.4676 | 28364 | -89.0556 |
| 2 | 0 | 0.01 | 1.75 | 1.051 | 0.4375 | 25552 | -88.1487 |
| 3 | 0 | 0.01 | 3 | 1.085 | 0.7122 | 21704 | -86.7310 |
| 4 | 0 | 0.03 | 0.5 | 0.933 | -0.5982 | 29805 | -89.4860 |
| 5 | 0 | 0.03 | 1.75 | 1.043 | 0.3708 | 26645 | -88.5125 |
| 6 | 0 | 0.03 | 3 | 1.079 | 0.6649 | 22836 | -87.1726 |
| 7 | 0 | 0.05 | 0.5 | 0.921 | -0.7135 | 30744 | -89.7553 |
| 8 | 0 | 0.05 | 1.75 | 1.039 | 0.3371 | 27771 | -88.8719 |
| 9 | 0 | 0.05 | 3 | 1.075 | 0.6322 | 23831 | -87.5430 |
| 10 | 0.1 | 0.01 | 0.5 | 0.595 | -4.4963 | 32314 | -90.1880 |
| 11 | 0.1 | 0.01 | 1.75 | 1.009 | 0.0788 | 33091 | -90.3943 |
| 12 | 0.1 | 0.01 | 3 | 1.054 | 0.4632 | 28397 | -89.0655 |
| 13 | 0.1 | 0.03 | 0.5 | 0.326 | -9.7304 | 28542 | -89.1099 |
| 14 | 0.1 | 0.03 | 1.75 | 0.976 | -0.2106 | 35163 | -90.9219 |
| 15 | 0.1 | 0.03 | 3 | 1.037 | 0.3166 | 30704 | -89.7442 |
| 16 | 0.1 | 0.05 | 0.5 | 0.324 | -9.7663 | 28871 | -89.2093 |
| 17 | 0.1 | 0.05 | 1.75 | 0.839 | -1.5228 | 37169 | -91.4038 |
| 18 | 0.1 | 0.05 | 3 | 1.004 | 0.0424 | 33623 | -90.5327 |
| 19 | 0.2 | 0.01 | 0.5 | 0.406 | -7.8291 | 30282 | -89.6239 |
| 20 | 0.2 | 0.01 | 1.75 | 0.972 | -0.2393 | 35289 | -90.9528 |
| 21 | 0.2 | 0.01 | 3 | 1.036 | 0.3101 | 30480 | -89.6805 |
| 22 | 0.2 | 0.03 | 0.5 | 0.315 | -10.0255 | 28370 | -89.0572 |
| 23 | 0.2 | 0.03 | 1.75 | 0.830 | -1.6158 | 36905 | -91.3418 |
| 24 | 0.2 | 0.03 | 3 | 0.999 | -0.0035 | 33446 | -90.4870 |
| 25 | 0.2 | 0.05 | 0.5 | 0.354 | -9.0143 | 29066 | -89.2679 |
| 26 | 0.2 | 0.05 | 1.75 | 0.858 | -1.3230 | 37250 | -91.4226 |
| 27 | 0.2 | 0.05 | 3 | 1.007 | 0.0669 | 33500 | -90.5011 |

The mean of means and of SN ratios are used to identify the best combination of factor levels allowing to improve the responses. The minimum values for the thickness varied from 0.315 mm to 1.085 mm. In Fig. 5, are reported the effects of the three factors on the thickness, using the means in Fig. 5a and the SN ratios in Fig. 5b. The results indicate that the friction coefficient (A) and the punch force (C) are the most significant factors affecting the thickness. Furthermore the clearance ratio, between the die and the blankholder, has a small contribution on the thickness and it can be concluded, that the minimum value of the thickness tends to decrease in a moderate way in passing from level 1 to level 3 of the clearance.



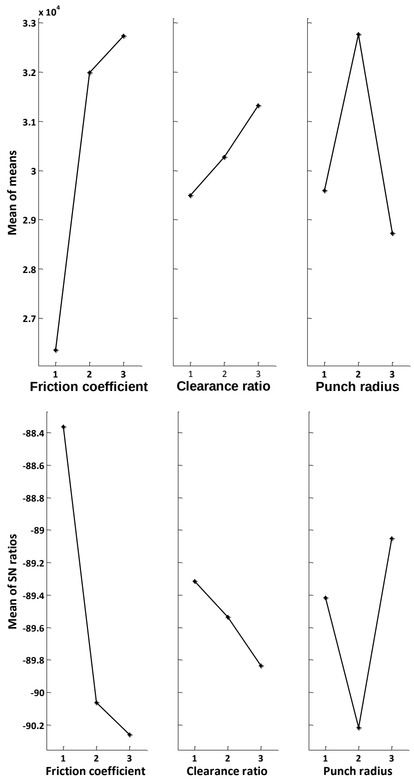

(a)




(b)

Fig. 5. Effects of the control factors on the thickness a) Thickness means and (b) SN ratio effects for each control factors.

The maximum values for the punch force varied from 21.7 kN to 37.17 kN. In Fig. 6, are reported the effects of the three control factors on the maximum value of the punch force, using the means in Fig. 6a and the SN ratios in Fig. 6b. The results indicate that the friction coefficient (A) is the significant factor affecting this response. Furthermore the clearance (B) has a small contribution and it can be shown, that this response is nonlinear according to the punch radius (C). The maximum value of the force is obtained for a punch radius at level 2. According to the results reported in Fig. 6, the best combination allowing to minimize the punch force is $A_1B_1C_3$. The results reported in Fig. 8, show that the same combination, $A_1B_1C_3$, allows to avoid severe thinning on the final workpiece, since the minimum values of thickness are increased.




(a) (b)

Fig. 6. Effects of the control factors on the punch force a) Punch force means and (b) SN ratio effects for each control factors.

The interactions (A×B and B×C) given in Fig. 7 and Fig. 8 could be neglected since the effect of clearance ratio (B) is low. Thus, the factor (B) could be set at any level to prolong the tool life depending on the need for the application. The interaction (A×C) is significant and must be considered mostly for low values of the punch radius (from level 1 to level 2). This interaction could be neglected for high values. The optimal combination for a high thickness and low punch force is $A_1B_1C_3$ within the tested range.

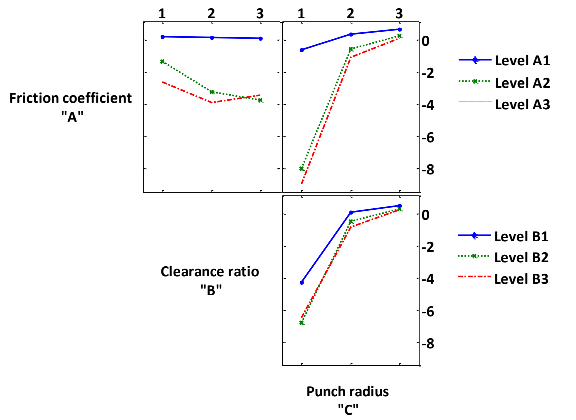



Fig. 7. Interaction plot for SN ratios obtained for thickness.

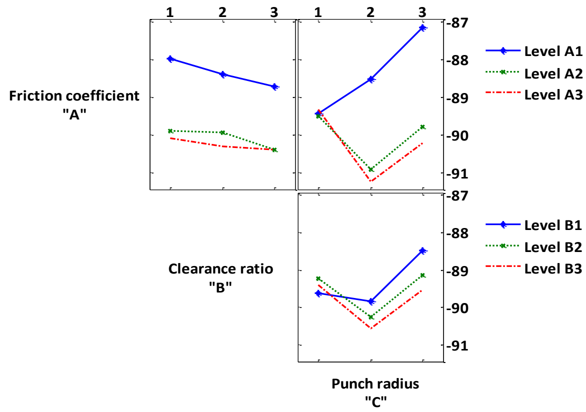



Fig. 8. Interaction plot for SN ratios obtained for punch force.

## *A. Recommended input factors*

The observed output parameters obtained from the model were sensitive to the friction coefficient, punch radius and blankholder factors. The sensitivity study allows to estimate the effect of variation in these factors in term of low, medium and high levels. A major variable that has an important effect contributes highly to the output parameters. However, a variable with an insignificant (low) sensitivity can be set to its theoretical mean value or any other constant value within its interval of variation. In order to determine which factors significantly affect the selected outputs, the S/N ratio based on the higher-the-better criterion were calculated and shown in Table 5 and Table 6. Rankings are based on difference between maximum and minimum value of each output through thickness and punch force. Thus, it can be deduced that the most sensitive's parameters are punch radius and friction coefficient.

Table 5. The response of the S/N ratios and their ranks (Thickness)

| Factors | Level 1 | Level 2 | Level 3 | Max-Min (Thickness) | Rank |
|---|---|---|---|---|---|
| PR | 17.54 | 1.22 | -1.06 | 18.6 | 1 |
| μ | -0.45 | 8.27 | 9.89 | 10.34 | 2 |
| BH | 3.67 | 6.94 | 7.08 | 3.41 | 3 |

Table 6. The response of the S/N ratios and their ranks (Punch force)

| factors | Level 1 | Level 2 | Level 3 | Max-Min | Rank |
|---|---|---|---|---|---|
| μ | -265 | -270.19 | -270.77 | 5.77 | 1 |
| PR | -268.25 | -270.65 | -267.15 | 3.5 | 2 |
| BH | -267.94 | -268.61 | -269.50 | 1.56 | 3 |

The sheet metal is subject mainly to three vertical forces during its forming: a punch force, matrix and the blankholder two opposite forces. The blankholder force directly depends on type of holding. The matrix force is the reaction of this one. Consequently, the thinning of the sheet metal strongly depends on the intensity and the correlation of these multiple forces. Low holding forces cause a sliding of the sheet. Otherwise, higher forces cause the localized thinning. The control of friction allows minimizing this undesirable effect by enable weak sliding of the sheet. Then, it's possible, for example, to establish a correlation between the matrix force and the friction. Also, a correlation can also be established between matrix and punch forces. Often, it is preferable to have high deformation energy and forces during deep forming process. However, a bad combination of friction and forces parameters causes several other manufacturing defects such as the wrinkiling, springback, crack etc.

The present article focuses on a numerical simulation study in order to obtain a minimum thinning. Consequently, recommended levels of input parameters can be proposed according to the following considered objectives: i- minimum localized thinning; ii- maximum punch force. Table 7 shows the recommended optimal input parameters:

Table 7. Recommended input factors.

| | μ | BH | PR |
|---|---|---|---|
| Min (localized thinning) | low | low | high |
| Max (punch force) | high | high | low |

## VI. CONCLUSIONS

In this study, it is carried out a design of experiments plan on deep drawing process in order to control localized thinning by varying three factors: friction coefficient, blankholder clearance and punch radius. The aim is to make a contribution to increase the product quality of the deep drawing process. The following main conclusions are drawn from this study:

In order to minimize the thinning of the blank, successful deep drawing depends mainly on friction coefficient and punch radius.

- The punch radius is recommended to be set at its highest level.

- The friction coefficient is recommended to be set at its lowest level.

- The blankholder clearance is recommended to be 10 times smaller than sheet thickness. If the clearance is not low enough, thinning will occur. Also, if the clearance is greater than the half of the sheet metal thickness, failure will occur.

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