Numerical simulation and experimental assessment for cold cylindrical deep drawing without blank-holder

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Abstract. The metal forming process through plastic deformation, represented by deep drawing, is an extremely vast research field. In this article we analyse the influence of the die punch clearance, the average velocity in the active phase as well as of the lubrication on the deep drawing quality revealed by the thickness evenness on the finished product surface. For thorough research and in order to minimize the number of experimental trials, a fractional factorial design of TAGUCHI type was developed attached to an orthogonal array, thus analysing the contribution of the three aforementioned parameters to the quality of cylindrical deep drawing without a blank holder. In order to compare the experimental results, a conceptual 3D model of the system punch-blank-die was made, which respects entirely the geometry of the active elements and of the blank, but schematizes/approximates the material properties of the blank. Thus, using these simulations, we can investigate the variation of the deformation parameters throughout the drawing process: from the initial blank form to the final drawn part. The numerical simulation of the drawing of cylindrical cups was made using the ANSYS V14 program, the Explicit Dynamic module. Using the signal-to-noise ratio suggested by TAGUCHI, we determined the influence of each of the three parameters under study on deep drawing quality, as well as their optimal values.

1. Introduction
The drawing process in general as well as the cylindrical deep drawing have been the object of study for numerous researchers, professors, postgraduates and engineers who used experiments and/or numerical simulations using various software programs.

Cold working is one of the modern methods, widely used in mechanical engineering, especially in fields like: automotive industry, aircraft industry, machine building, electrical and household appliances manufacturing, agricultural machinery industry and others. One of its very important advantages is that of achieving very high work productivity due to mechanization and automation of the working processes [1].

Cold working offers allows getting parts of various shapes, from the simplest to those with a high degree of complexity whose manufacturing through other methods is uneconomical, difficult and sometimes even impossible [2].

The material used is in the shape of a 1 mm thick metal sheet. It is to be mentioned that the material used to study the drawing process is a common material which does not fall into the category of special materials for deep drawing. However, its physical and mechanical properties meet the general requirement that the material should be easily deformable, having high plastic deformation and low necking.

The research work for this paper strongly intertwines the theoretical study and the experimental one. Using theoretical studies we get mathematical modelling of different parameters that characterize the deep drawing of cylindrical cups.

In the current article, the research appeals to a design of experiments using the Taguchi method for an optimal set of factors influencing the deep drawing of cylindrical cups.
The strategy adopted by Taguchi is rather opposite: instead of trying to eliminate these parasite factors (also named the noise factors), he tried to minimize their impact. Concretely, the method consists in identifying the combinations of parameters that decrease the cause’s effects, without attacking them directly [3].

The Taguchi experience plans use simultaneously, as performance indicators, the Signal/Noise ratios, which take into account, simultaneously: the desired value (the signal) to achieve and the undesired variable of this value (the noise) to be fought against.

To implement the Taguchi method, the following steps have to be made: defining the experimenting goal; selecting the controlled factors and the values to be tested; selecting the design of experiments to be used; doing the experiments and recording the results; analysing the results and determining the configuration which ensures their optimization and undergoing validation trials for the configuration which ensures optimization [3].

Concluding, we can assert that a design of experiments is optimum when we get maximum precision with minimum number of trials.

2. The experiments of the cylindrical cup drawing

2.1. The influence of the die punch clearance, the average velocity and the lubrication on the deep drawing quality

The Taguchi designs of experiments determine both the average (as in the “traditional” method) and the variability of the values of the measured features.

When making a design of experiments to determine a feature (in our case the variation of the wall thickness in the drawn part in significant points), we must state: the determinant factors, the value levels attributed to each factor and the total number of trials $N_T$.

The experiments were done using a HP-U60R hydraulic press with maximum pressing force of 600 KN, with electrohydraulic control from the control panel, destined for processes like drawing, bending, stamping, flattening, depicted in figure 1.

![Figure 1. Photo of the die used in studying the deep drawing of cylindrical cups.](image)

The deep drawing process is done by hydraulic action of the punch that deforms the blank, the latter being pushed into the die and taking its shape. The main geometric elements of the punch-blank-die ensemble are rendered in figure 2, while their dimensions are shown in table 1.
Table 1. Basic geometrical parameters.

| Parameter                  | Dimension (mm) |
|----------------------------|----------------|
| Blank size radius (BR)     | 38.5           |
| Blank thickness (g)        | 1              |
| Punch radius (PR)          | 21.5           |
| Punch nose radius (rp)     | 12             |
| Die radius (DR)            | 23.1           |
| Die shoulder radius (rd)   | 6              |

Figure 2. The geometric elements of the deep drawing process.

For the experiments we used disc shaped brass blanks CW508L, having 77 mm in diameter and 1 mm thickness, its mechanical properties being shown in table 2. The experiments involved three punches with different diameters in order to determine the variation of the radius clearance.

We consider deep drawing that deformation which has the LDR drawing coefficient over 1.72. For the CW508L material used in this study, the LDR value is between 1.59 ÷ 1.60 for the first drawing operation [4]. For this reason an additional drawing operation was needed to meet the condition for deep drawing.

Considering the technical conditions for the experiments, we will consider the experimental designs for three representative control factors: 1° - the clearance between the active elements (die - punch); 2° - the moving velocity of the hydraulic press ram 3° - the presence or the absence of lubrication.

Table 2. Mechanical properties for the brass sheet CW508L.

| Brand   | Tensile yield strength $R_{p0.2}$ (MPa) | Ultimate tensile strength $R_m$ (MPa) | Poisson Coefficient $n_{med}$ | Longitudinal A (%) | Across A (%) |
|---------|----------------------------------------|--------------------------------------|-------------------------------|---------------------|--------------|
| CW508L  | 210                                    | 410                                  | 0.3                           | 20                  | 47.5         |
For the quantitative determination of the dimensional quality of the drawn parts, consisting in the evenness of the wall and bottom thickness, we choose 12 points where the measuring is done, 7 points numbered 1÷7, on the side wall of the part, point number 8 being chosen in the area of transition between the wall and the bottom, while points 9÷12 are on the bottom of the part (figure 2). The measurements in the 12 points for the thickness of the parts were done using an ultrasound device, Sonatest T- Gage IV MM.

![Figure 3. Points of thickness variation measurements.](image)

We aim at developing a representative set of experiments regarding cylindrical drawing according to the experimental design rendered by the orthogonal array $\hat{L}_9$ that is characterized by 1 factor with 2 levels and 2 factors with 3 levels (table 4), analyzing the influence of the three parameters (table 4) on the thickness variation of a drawn part.

The purpose of the research done in the paper using the Taguchi method is to determine the influence of the drawing parameters and to identify the relative influence of each analyzed parameter for the process in question.

The plan of experiments has been conceived in such a way that it would be rendered by an experimental trial array (E) with $N_F$ columns, having one column for each determinant factor and n lines, one row for each experimental trial, having as elements the ordinal numbers of the level for each of the NF factors.

Due to the advantage of minimizing the total number of experiments (n), the orthogonal experimental matrix, presented in table 5, has been adopted.

It is noticeable that two of the controlled factors $J_{mp}$ and V, have 3 levels, but one of the factors, U/FU, can actually receive only 2 levels. To integrate the U/FU factor in the fractional experiments array with 3 standard levels L9 (4 factors with 3 levels), it must be formally treated as a factor with 3 levels. To this end, we assigned the first column of the L9 array to the U/FU factor and level 3 from the experiments 7÷9 was replaced by level 1 from the experiments 7 and 9 and, respectively, by level 2 in experiment 8. Then, the columns 3 and 4 of the L9 array were assigned to the factors $J_{mp}$ and V and in this way we got the experiments array depicted in the table 4.

### Table 3. The values assigned to the control factors in the design of experiments.

| No. | Symbol | Name                      | (M.U.)  | 1   | 2   | 3   |
|-----|--------|---------------------------|---------|-----|-----|-----|
| 1   | U/FU   | Lubrication               | -       | U   | FU  | -   |
| 2   | $J_{mp}$ | Die punch clearance      | (mm)    | 0.60| 1.10| 1.35|
| 3   | V      | Average velocity         | (mm/s)  | 1.193| 2.982| 4.175|
Table 4. The design of experiments rendered by the orthogonal array \( L_9 \)

| Experiment | The controlled factor |
|------------|-----------------------|
|            | \( U/FU \) | \( Jmp \) | \( V \) |
| 1          | 1          | 1          | 1          |
| 2          | 1          | 2          | 2          |
| 3          | 1          | 3          | 3          |
| 4          | 2          | 2          | 3          |
| 5          | 2          | 3          | 1          |
| 6          | 2          | 1          | 2          |
| 7          | 1          | 3          | 2          |
| 8          | 2          | 1          | 3          |
| 9          | 1          | 2          | 1          |

In table 5, for each experiment, the following have been evaluated and stored: \( g \) is averages of thickness, \( \sigma \) is standard deviation and \( S/N \) is signal / noise ratio,

\[
S/N = 10 \cdot \log \left( \frac{(g/\sigma)^2}{1/n} \right) \text{ (dB)}
\]

(1)

Where \( n \) is the number of experimental trials (\( n = 9 \)); dB is decibels - measurement unit for a dimensionless quantity [5].

Further processing the data in table 5 – lines 13 to 15, the following averages have been evaluated, respectively:

\( \tilde{g} \) is general averages of thickness,

\[
\tilde{g} = \frac{1}{n} \sum_{i=1}^{n} g_i = 1.0369 \text{ mm}
\]

(2)

\( \bar{\sigma} \) is average standard deviation,

\[
\bar{\sigma} = \frac{1}{n} \sum_{i=1}^{n} \sigma_i = 1.1980 \text{ mm}
\]

(3)

The mean value for the signal / noise ratio has been calculated using [3, 5]:

\( \overline{S/N} \) is average signal / noise ratio,

\[
\overline{S/N} = \frac{1}{n} \sum_{i=1}^{n} (S/N)_i = 14.3722
\]

(4)

The optimal performance of the deep drawing process is identified in experiment 6 and corresponds to the maximum value for the ratio dB, and respectively to the minimum value for the deviation \( \sigma \), \( \sigma_6 = 0.1813 \text{ mm} \).

Reconsidering data in table 4, for each of the three parameters and for each of their value levels, we determined the ordinal numbers of the experiments (table 6).

The arithmetic means for each parameter and its corresponding level have been determined, the results being stored in table 7.

\[
SS = \sum_{i=1}^{n} \left[ (S/N)_i - \overline{S/N} \right]^2 = 0.7967
\]

(5)
Table 5. The experimental values for the wall and bottom thickness measured after the second drawing for CW508L (mm).

| Point position | Number of experiment, i |
|----------------|-------------------------|
| 1              | 1.40 1.41 1.42 1.40 1.41 1.39 1.42 1.39 1.41 |
| 2              | 1.30 1.31 1.31 1.30 1.30 1.28 1.30 1.29 1.30 |
| 3              | 1.17 1.16 1.27 1.15 1.26 1.16 1.28 1.27 1.15 |
| 4              | 1.09 1.12 1.19 1.11 1.18 1.09 1.20 1.08 1.12 |
| 5              | 1.05 1.09 1.08 1.10 1.09 1.06 1.08 1.05 1.09 |
| 6              | 0.92 0.94 0.97 0.95 0.98 0.93 0.98 0.94 0.94 |
| 7              | 0.90 0.90 0.90 0.91 0.92 0.92 0.91 0.90 0.91 |
| 8              | 0.84 0.86 0.86 0.87 0.87 0.85 0.86 0.85 0.86 |
| 9              | 0.85 0.87 0.87 0.88 0.88 0.86 0.87 0.86 0.87 |
| 10             | 0.85 0.87 0.88 0.89 0.89 0.88 0.88 0.87 0.88 |
| 11             | 0.87 0.87 0.89 0.89 0.90 0.88 0.88 0.89 0.89 |
| 12             | 0.87 0.87 0.89 0.89 0.90 0.88 0.88 0.89 0.89 |

\( \bar{g}_i, \text{(mm)} \) = 1.0092 1.0225 1.0442 1.0283 1.0483 1.0150 1.0450 1.0233 1.0258

\( \sigma_i, \text{(mm)} \) = 0.1929 0.1924 0.2024 0.1817 0.1927 0.1813 0.2034 0.1927 0.1863

\( (S/N)_i, \text{(dB)} \) = 14.360 14.498 14.239 15.044 14.701 14.948 14.201 14.492 14.804

Table 6. Experiment number for process parameters and their ordered levels

| Level | Experiment No. | Level | Experiment No. | Level | Experiment No. |
|-------|----------------|-------|----------------|-------|----------------|
| 1     | 1              | 1     | 1              | 1     | 1              |
| 1     | 2              | 1     | 6              | 1     | 5              |
| 1     | 3              | 1     | 8              | 1     | 9              |
| 1     | 7              | 2     | 2              | 2     | 2              |
| 1     | 9              | 2     | 4              | 2     | 6              |
| 2     | 4              | 2     | 9              | 2     | 7              |
| 2     | 5              | 3     | 3              | 3     | 3              |
| 2     | 6              | 3     | 5              | 3     | 4              |
| 2     | 8              | 3     | 7              | 3     | 8              |

Table 7. Level averages of S/N ratio for each parameter.

| Level | \( U/FU \) | \( J_{mp} \) | \( V \) |
|-------|------------|--------------|--------|
| j     | \( S/N_{U/Fj} \) | \( n_{U/Fj} \) | \( S/N_{J_{mp}j} \) | \( n_{J_{mp}j} \) | \( S/N_{Vj} \) | \( n_{Vj} \) |
| 1     | 14.4204    | 3            | 14.5999 | 2            | 14.6216 | 2            |
| 2     | 14.7964    | 3            | 14.7822 | 2            | 14.5493 | 2            |
| 3     | -          | 0            | 14.3805 | 2            | 14.5917 | 2            |

For each process parameter, the sums of squares due to variation of the mean, and their contributions on the deep-drawing process are [6, 7]:
The results of the calculations for all the above quantities are stored in table 8.

|   | U/FU | Jmp | V   |
|---|------|-----|-----|
| SS<sub>U/F</sub> | 0.2146 | 0.1618 | 0.0053 |
| C<sub>U/F</sub>, (%) | 56.2292 | 42.3867 | 13.0401 |

In the figure 4 shows the deviation from the thickness of the half-finished material in the 12 measurement points for the experiments number 6 and 7.

![](image)

**Figure 4.** The deviation from the thickness of the semifinished material for the experiment No. 6 and No. 7.

### 3. Simulation of Deep Drawing Process

#### 3.1. Finite Element Model

To validate both the mathematical model based on FEM and the accuracy of the software used, the results of the numerical simulations must be compared to the experimental results. The program used is structured on three general components: pre-processing, analysis and post-processing.

In the pre-processing stage a conceptual 3D model of the system punch (1) – blank (2) – die (3) was made, which respects entirely the geometry of the active elements and of the blank (figure 5).
The physical-mechanical properties of the material of the blank used for the experiments (table 2.) were fed into the materials library of the software using the Engineering Data – Edit command. Choosing the contact areas between the active elements and the blank is the next step within the pre-processing stage. We identify an area between the punch and the blank as well as an area between the blank and the die. During the same stage, we choose the discretization of the active elements of the punch-die ensemble, the value (size) of the element within the network being 5 mm, while for the blank the size of the element is 1 mm (figure 6.).

The choices of the die as a fixed holder, the punch as a motion element and its direction, represent the conditions introduced into the simulation of the cylindrical deep drawing. Using this 3D model and employing the finite element method, we performed numerical simulations of the blank behaviour during deformation, highlighting the following features: the deformation velocity, the direction of the deformations, the degree of thinning / thickening of the material undergoing these deformations. The analysis of the thickness variation for the parts made after simulation, is done in the same conditions as in the case of the experimental study, for various clearances (j=0.60; j=1.10; j=1.35mm). The radial clearance is a very important parameter in the drawing process, being defined as the difference between the die radius and the punch radius (j = DR - PR).

The thickness variation measuring is done by locating the reference knots corresponding to the model
in figure 7. It is obvious that these points cannot be exactly located due to discretization and to the measuring errors in the experimental trials, so, it is to be expected that small variations of thickness will occur [8].

Figure 7. The measuring points for the thickness variation for validating the model.

4. Results and discussions
In the cylindrical deep drawing process, we achieved experimentally three sets of samples of brass CW508L. The drawing process was based on a design of experiments materialized through the use of the orthogonal array $\tilde{L}_9$, respecting the Taguchi method.

In order to analyze the thickness variation for brass CW508L, we compare the average values of the thickness achieved experimentally with the ones determined through simulation using the Ansys software package. The average variation of the experimental thickness was determined from the values of three samples for the three radial clearances considered (tables 9, 10, 11).

The comparison of the thickness variation was done for the radial clearances $j = 0.60$ mm (figure 8.), $j = 1.10$ mm (figure 9) and $j = 1.35$ mm (figure 10), representing graphs which are characterized by three distinct areas. The first area is defined by a thickening of the material in the superior part of the part (point 1), followed by a decrease corresponding to points 2 – 7, and then the area of maximum thinning of the material characteristic to point 8 (risk area). Finally, we notice a slight increase of the thickness on the bottom of the part.

Table 9. Thickness variation determined experimentally and after simulation with finite element CW508L for $j = 0.60$ mm.

| Point location | Experimental thickness Sample 1 (mm) | Experimental thickness Sample 2 (mm) | Experimental thickness Sample 3 (mm) | Average thickness (mm) | Simulation thickness FE (mm) |
|----------------|-------------------------------------|-------------------------------------|-------------------------------------|------------------------|-----------------------------|
| 1              | 1.40                                | 1.40                                | 1.42                                | 1.407                  | 1.6784                      |
| 2              | 1.30                                | 1.30                                | 1.30                                | 1.300                  | 1.5366                      |
| 3              | 1.17                                | 1.15                                | 1.28                                | 1.200                  | 1.3829                      |
| 4              | 1.09                                | 1.11                                | 1.20                                | 1.133                  | 0.9864                      |
| 5              | 1.05                                | 1.10                                | 1.08                                | 1.077                  | 0.8599                      |
| 6              | 0.92                                | 0.95                                | 0.98                                | 0.950                  | 0.7562                      |
| 7              | 0.90                                | 0.91                                | 0.91                                | 0.907                  | 0.7371                      |
| **8**          | **0.84**                            | **0.87**                            | **0.86**                            | **0.857**              | **0.6871**                  |
| 9              | 0.85                                | 0.88                                | 0.87                                | 0.867                  | 0.7206                      |
| 10             | 0.85                                | 0.89                                | 0.88                                | 0.873                  | 0.7639                      |
| 11             | 0.87                                | 0.89                                | 0.88                                | 0.880                  | 0.7814                      |
| 12             | 0.87                                | 0.89                                | 0.88                                | 0.880                  | 0.8347                      |
Table 10. Thickness variation determined experimentally and after simulation with finite element CW508L for \( j=1.10 \) mm.

| Point location | Experimental thickness Sample 1 (mm) | Experimental thickness Sample 2 (mm) | Experimental thickness Sample 3 (mm) | Average thickness (mm) | Simulation thickness FE (mm) |
|----------------|-------------------------------------|-------------------------------------|-------------------------------------|------------------------|-----------------------------|
| 1              | 1.41                                | 1.41                                | 1.39                                | 1.403                  | 1.6443                      |
| 2              | 1.31                                | 1.30                                | 1.29                                | 1.300                  | 1.5357                      |
| 3              | 1.16                                | 1.26                                | 1.27                                | 1.230                  | 1.4886                      |
| 4              | 1.12                                | 1.18                                | 1.08                                | 1.127                  | 1.3193                      |
| 5              | 1.09                                | 1.09                                | 1.05                                | 1.077                  | 1.2872                      |
| 6              | 0.94                                | 0.98                                | 0.94                                | 0.953                  | 1.1054                      |
| 7              | 0.90                                | 0.92                                | 0.90                                | 0.907                  | 0.8587                      |
| 8              | 0.86                                | 0.87                                | 0.85                                | 0.860                  | 0.7142                      |
| 9              | 0.87                                | 0.88                                | 0.86                                | 0.870                  | 0.7269                      |
| 10             | 0.87                                | 0.89                                | 0.87                                | 0.877                  | 0.7512                      |
| 11             | 0.87                                | 0.90                                | 0.89                                | 0.887                  | 0.7731                      |
| 12             | 0.87                                | 0.90                                | 0.89                                | 0.887                  | 0.8142                      |

Table 11. Thickness variation determined experimentally and after simulation with finite element CW508L for \( j=1.35 \) mm.

| Point location | Experimental thickness Sample 1 (mm) | Experimental thickness Sample 2 (mm) | Experimental thickness Sample 3 (mm) | Average thickness (mm) | Simulation thickness FE (mm) |
|----------------|-------------------------------------|-------------------------------------|-------------------------------------|------------------------|-----------------------------|
| 1              | 1.42                                | 1.39                                | 1.41                                | 1.407                  | 1.6885                      |
| 2              | 1.31                                | 1.28                                | 1.30                                | 1.297                  | 1.5431                      |
| 3              | 1.27                                | 1.16                                | 1.15                                | 1.193                  | 1.4973                      |
| 4              | 1.19                                | 1.09                                | 1.12                                | 1.133                  | 1.3227                      |
| 5              | 1.08                                | 1.06                                | 1.09                                | 1.077                  | 1.2754                      |
| 6              | 0.97                                | 0.93                                | 0.94                                | 0.947                  | 1.0955                      |
| 7              | 0.90                                | 0.92                                | 0.91                                | 0.910                  | 1.0629                      |
| 8              | 0.86                                | 0.85                                | 0.86                                | 0.857                  | 0.7120                      |
| 9              | 0.87                                | 0.86                                | 0.87                                | 0.867                  | 0.7251                      |
| 10             | 0.88                                | 0.88                                | 0.88                                | 0.880                  | 0.7284                      |
| 11             | 0.89                                | 0.88                                | 0.89                                | 0.887                  | 0.8275                      |
| 12             | 0.89                                | 0.88                                | 0.89                                | 0.887                  | 0.8592                      |

Figure 8. The comparison between the average thickness determined experimentally with the thickness determined through simulation with the FE for \( j=0.60 \) mm, for brass CW508L.
5. Conclusions

Using the orthogonal array, a number of 9 experiments were undergone, doing 12 measurements in different points for each experiment.

For the analysed case, the highest influence is that of lubrication, U/FU, (56.2292%), followed by the contribution of the punch – die clearance, \( J_{mp} \) (42.3867 %), while the lowest contribution (13.0401 %) belongs to the average velocity in the active phase, \( V \).

The optimal values attributed to the control factors are the ones corresponding to experiment 6, where the standard deviation of thickness \( \sigma_i = 0.1813 \) mm is minimum, as opposed to the maximum standard deviation of thickness \( \sigma_i = 0.2034 \) mm corresponding to experiment 7.

For brass CW508L, we notice a material thickening of 40.56% compared to the original thickness of the blank, at the free end of the part. There is also a material thinning of 15.38% compared to the initial thickness at the intersection of the lateral wall with the bottom of the part, called joint area, corresponding to the measurement point number 8. The part preserves its thickness, corresponding to the measurement point 5, situated at 2/3 of the distance from the free end and 1/3 from the bottom.

The error margin noticeable after comparing the experimentally determined average thickness and the thickness determined through simulation with finite element, for brass CW508L, is ±17.02%.
This comparison is made for clearances $j=0.60$, $j=1.10$ and $j=1.35$ mm, being depicted in diagrams characterized by three distinct areas. The first area is characterized by a material thickening in the superior part of the drawn part (point 1), followed by a decrease (points 2 – 7), and then the maximum material thinning area corresponding to point 8 (risk area), then we notice a slight increase of the thickness on the bottom of the part. The error margin occurring after comparing thickness variation in the two cases, is justified by the fact that in the case of the simulation with finite element, the blank material was considered axially-symmetric anisotropic. In reality, the properties of the blank material may vary on the radial direction due to the lamination process.

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