

# NUMERICAL ANALYSIS OF SHEET METAL FORMING: THE CORRUGATION EFFECT

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**Abstract:** A new approach to solving the problem of the sheet-flange corrugation in the process of forming cylindrical sheet-metal elements is presented. A brief characteristic of the dynamic central-difference method is given. Technological parameters of a forming disk, a die block and a plunger die have been selected from references. Sample results of computer simulations with stress distributions in a disk are presented and serve as the basis for discussing the process of sheet metal forming.

**Keywords:** FEM, corrugation, drawing, blankholder

## 1. Introduction

The process of sheet metal forming is marked by many unfavorable phenomena. One of the most common problems is corrugation of sheet metal before passing the cutting edge of the die block. It results mainly from strong circumferential strains on the drawn cup rim [1]. These strains are produced by compressive stress, which bring about corrugation of the flange when the sheet is too thin. The simplest preventive measure is to increase the die block's radius which reduces the circumferential strain speed to radial strain speed ratio. However, an excessively increased radius brings about a decrease in the surface of contact with the die block, which may lead to the further corrugation. The problem of sheet metal corrugation is generally absent in the case of forming thicker steel sheets, where the thickness/diameter ratio is greater than 0.015 [2].

The best preventive measure against sheet metal corrugation is to apply a blankholder (Figure 1). Its function consists in pressing the sheet to the die's surface until the flange passes through its rounded edge.

The present work puts forwards an application of the finite element method to analyze sheet metal forming allowing for the corrugation effect. Two analyses of the same parameters have carried out: one with no blankholder applied, in order to

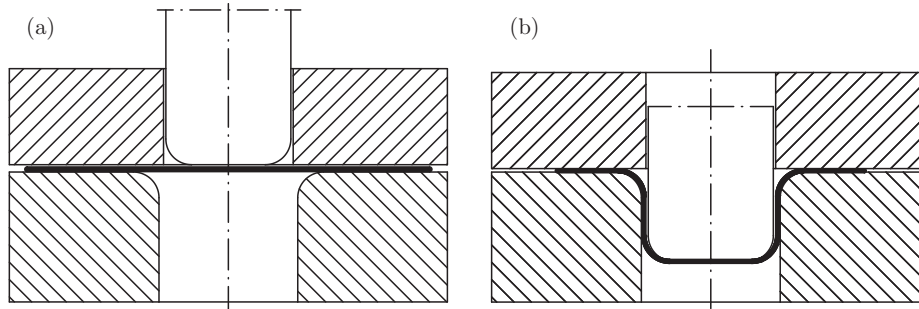


Figure 1. Diagram of sheet metal forming with a blankholder:  
(a) initial phase; (b) final phase

observe the unfavorable corrugation effect, the other with pad pressing with a specific force. Data for the calculations have been determined on the basis of the proposed methodology.

## 2. Selecting the method for calculations

This transient problem was approached using the central-difference method, also referred-to as the explicit-integration method. It includes a larger group of methods for direct integration of dynamic equations of motion.

The equation describing an object's motion at a typical time step in updated Lagrange's description assumes the following form:

$$\begin{aligned}
 & [M]\{\Delta\ddot{\mathbf{r}}\} + [C_T(\cdot)]\{\Delta\dot{\mathbf{r}}\} + ([K_T(\cdot)] + [\Delta K_T(\cdot)])\{\Delta\mathbf{r}\} = \\
 & \{\Delta R_T(\cdot)\} + \{\Delta F(\cdot)\} + \{F_T(\cdot)\},
 \end{aligned} \tag{1}$$

where:

- $[M]$  – global system-mass matrix at time  $t$ ,
- $[C_T]$  – global system-attenuation matrix at time  $t$ ,
- $[K_T]$  – global stiffness-increment matrix at time  $t$ ,
- $[\Delta K_T]$  – global object stiffness matrix at the step,
- $\{F_T\}$  – global object intrinsic load vector at time  $t$ ,
- $\{\Delta F\}$  – object intrinsic load increment vector,
- $\{\Delta R_T\}$  – global object external load increment vector,
- $\{\Delta\mathbf{r}\}$  – object site dislocation increment vector,
- $\{\Delta\dot{\mathbf{r}}\}$  – object site velocity increment vector,
- $\{\Delta\ddot{\mathbf{r}}\}$  – object site acceleration increment vector.

Equation (1) is integrated with respect to time step by step and is not rearranged before this operation. If system displacements, velocities and accelerations are assumed to be known at time  $\tau = t_0$  and respectively equal  $\{\mathbf{r}_0\}$ ,  $\{\dot{\mathbf{r}}_0\}$ ,  $\{\ddot{\mathbf{r}}_0\}$ , the whole interval is divided into parts  $\Delta t$  in length and each step is used for searching the solution to Equation (1). In other words, the equation can be satisfied only at selected moments of time, but not in the whole tested interval. This means that balance points of systems affected by external, inertial and attenuation forces could be searched for each moment using the algorithms of statistical analysis. The end of each moment of time is simultaneously the beginning of the next moment [3]. However, the equation is not solvable due to number of unknowns exceeding the number of equations. With

n equations of motion at our disposal,  $3n$  of  $\{\dot{\mathbf{r}}\}$  and  $\{\ddot{\mathbf{r}}\}$  unknowns are searched for. An approximation by the central-difference method has been applied to express  $\{\dot{\mathbf{r}}\}$  and  $\{\ddot{\mathbf{r}}\}$  vectors using the displacement vectors at moments  $t - \Delta t$ ,  $t$ ,  $t + \Delta t$ . This method, which can produce an approximate result only, consists in presenting velocity and acceleration by means of displacement according to the following formulas:

$$\{\dot{\mathbf{r}}^t\} = \frac{1}{2\Delta t} (\{\mathbf{r}^{t+\Delta t}\} - \{\mathbf{r}^{t-\Delta t}\}), \tag{2}$$

$$\{\ddot{\mathbf{r}}^t\} = \frac{1}{\Delta t^2} (\{\mathbf{r}^{t+\Delta t}\} - 2\{\mathbf{r}^t\} + \{\mathbf{r}^{t-\Delta t}\}). \tag{3}$$

The central-difference method does not require reversing the stiffness matrix  $[\mathbf{K}]$ , which is an advantage, especially with undiagonal mass and attenuation matrixes. However, its fundamental disadvantage is a lack of unconditional algorithm stability, which requires the selection of the step length after time  $\Delta t$  so that it is smaller than the critical time,  $\Delta t_{kr}$ , depending on the system's properties. ANSYS LS-DYNA has an option of automatic length selection for each step, which makes it more user-friendly.

### 3. Selecting conditions for sheet metal forming

The following conditions for sheet metal forming were admitted [4]:

- $D_0 = 70\text{mm}$  – initial disk diameter,
- $d = 40\text{mm}$  – diameter of a cylindrical wall of drawn cups (assumed),
- $g_0 = 1\text{mm}$  – disk thickness,
- $d_m = 41\text{mm}$  – diameter of a die-block hole,
- $d_s = 38.4\text{mm}$  – diameter of a plunger die,
- $r_m = 9\text{mm}$  – diameter of die-block edge rounding,
- $r_s = 5\text{mm}$  – diameter of plunger-die edge rounding,
- $\mu = 0.1$  – coefficient of friction between the sheet metal and the die block,
- $r_m = 18\text{mm}$  – diameter of die-block edge rounding,
- $P_{doc} = 500\text{N}$  – compressive force of a blankholder,
- $R_m = 350\text{MPa}$  – tensile strength of sheet-metal.

The diameter of a plunger die was obtained from the following relations:

$$d_s = d_m - 2 \cdot g_{\max}, \tag{4}$$

$$g_{\max} = g_0 \cdot (D_0/d)^b, \tag{5}$$

where:

- $g_{\max}$  – maximum thickness of a drawn cup at the edge [mm],
- $g_0$  – initial thickness of sheet metal [mm],
- $D_0$  – disk diameter [mm],
- $d$  – drawn cup diameter [mm],
- $b$  – exponent of standard anisotropy (isotropic sheet metal 0.5).

The radius of working-edge rounding was obtained from:

$$6 < r_m/g < 12, \tag{6}$$

$$6 < r_m < 12, \tag{7}$$

$$4g < r_s < 6g, \tag{8}$$

$$4 < r_s < 6, \tag{9}$$

yielding  $r_m = 9\text{mm}$  and  $r_s = 5\text{mm}$ .

According to [1], a blankholder is required in order to prevent corrugation in case of the following inequality:

$$g_0/D_0 < 0.04 \cdot (1 - d/D_0), \quad (10)$$

where:

$g_0$  – sheet metal thickness [mm],

$D_0$  – disk diameter [mm],

$d$  – diameter of a cylindrical wall of drawn cups [mm].

The force of the blankholder is calculated from the formula:

$$P_{\text{doc}} = 0.0004 \cdot b \cdot (D_0 - b) \cdot (b/g) \cdot R_m, \quad (11)$$

where:

$P_{\text{doc}}$  – compressive force of a blankholder [N],

$b$  – initial width of a flange flat section [mm],

$D_0$  – disk diameter [mm],

$g$  – sheet-metal thickness [mm],

$R_m$  – tensile strength of sheet metal [MPa],

$r_m$  – diameter of die-block edge rounding [mm].

Since condition (10) is fulfilled in this case, as  $0.0143 < 0.0171$ , it is necessary use a blankholder. The initial width of the flat section of a flange amounts to  $b = 0.5 \cdot (D_0 - d) - r_m = 0.5 \cdot (70 - 40) - 9 = 6$  mm, while the compressive force equals  $P_{\text{doc}} = 0.0004 \cdot 6 \cdot (70 - 6) \cdot (6/1) \cdot 350 = 322$  N. Considering that it is a minimum value of the required compressive force and an analytical result, the value of the compressive force has been increased to 500 N.

#### 4. Selecting the numerical parameters

A material model with power-expressed non-linear strengthening was selected for numerical analysis. This model has no sharp yield point and represents the stress/strain relation much better than a bilinear model, which reveals linear flexibility expressed by Young's modulus and linear strengthening. Stress was expressed in the material model by the following formula (see Figure 2):

$$\sigma_p = K \cdot (\varepsilon_0 + \varepsilon_i)^n, \quad (12)$$

where:

$\sigma_p$  – value of stresses [MPa],

$K$  – the strengthening constant [MPa],

$\varepsilon_0$  – initial strain,

$\varepsilon_i$  – strain intensity,

$n$  – the strengthening exponent.

The following values were assumed for calculations:  $K = 610$  MPa,  $\varepsilon_0 = 0$  and  $n = 0.22$ .

The following parameters for a material model of the forming disk were assumed [4]:

$\rho = 7800$  kg/m<sup>3</sup> – density,

$E = 210$  GPa – Young's modulus,

$\nu = 0.29$  – Poisson's ratio.

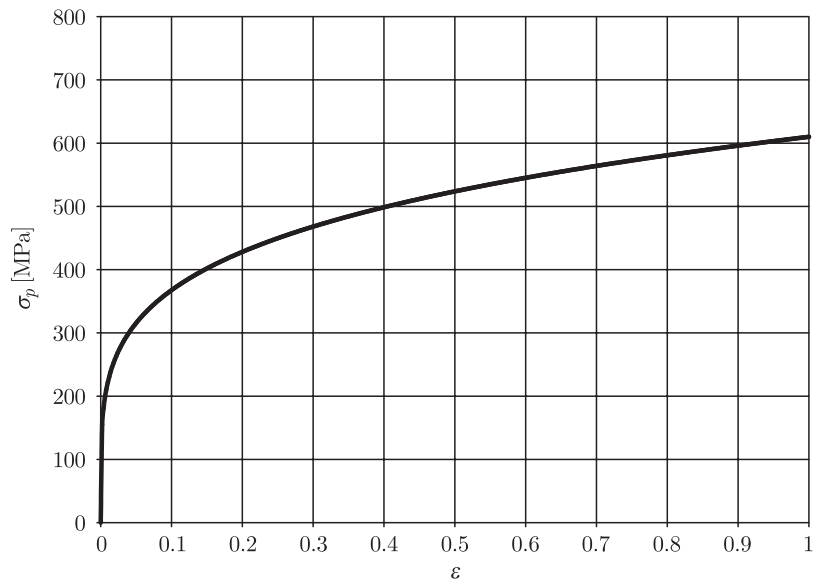


Figure 2. The material model applied to simulations

The tools used in the process of sheet metal forming, *i.e.* a die block and a plunger die were assumed to be non-deformable bodies. A discrete model of the object is shown in Figure 3. The disk was sectioned with elements of the solid type enabling observation of the phenomena occurring inside the sheet metal. However, the die block and the plunger die were sectioned with elements of the shell type, as in this case the intrinsic phenomena were not subjected to investigations.

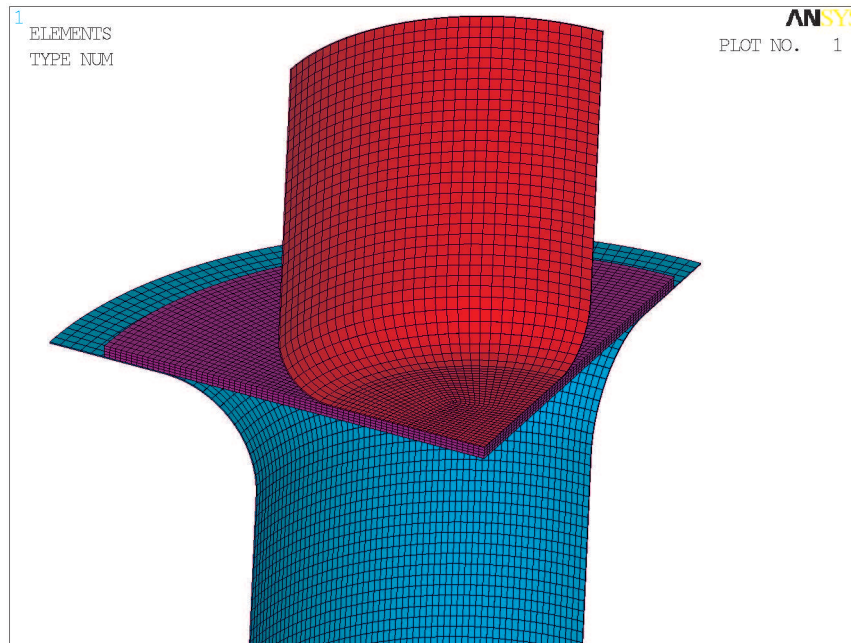


Figure 3. A discrete model of the object

## 5. Findings of numerical analysis without a blankholder

At the initial stage of press forming, the sheet-metal deformation was proceeding smoothly (Figure 4a). There appeared stresses of the order of 350MPa in the area of bending the sheet metal on the rounded die edge. A compression stress of approximately 133MPa occurred in the region of direct contact between the sheet metal and the rounded plunger edge. This region underwent the slightest deformation during the whole process.

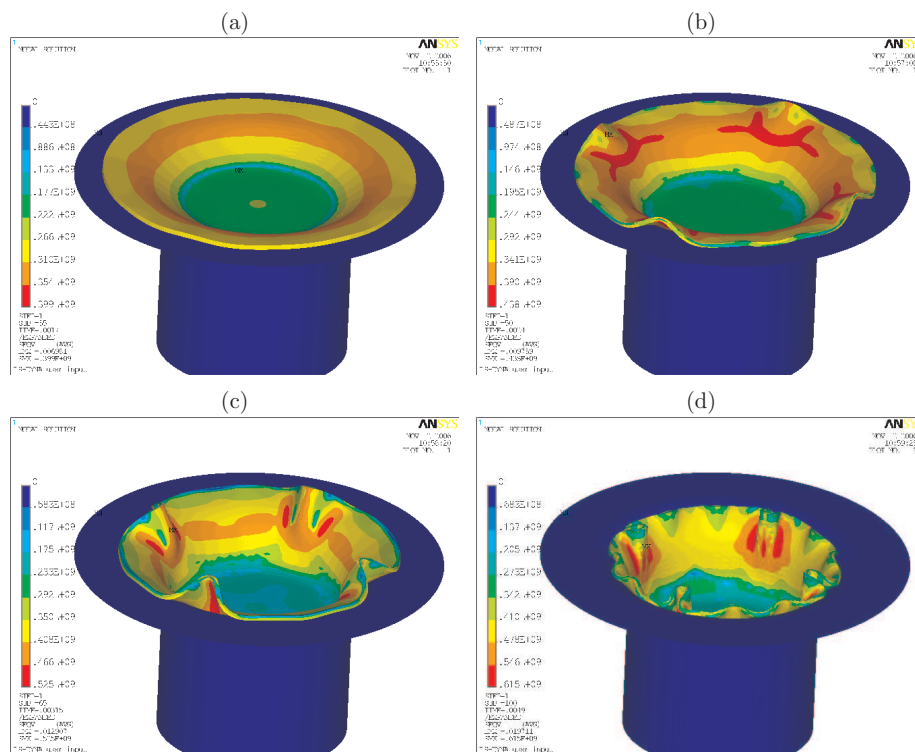


Figure 4. Findings of numerical analysis without a blankholder

During the next stage of the process (Figure 4b) the appearance of compressive circumferential stresses reaching the value of 438MPa was observed. This value exceeded the critical value of the bifurcation point, which led to elastic buckling of the sheet metal. Then a part of the metal sheet tore off the working surface of the die and the other part increased its pressure on this surface. With thicker sheet metal, the critical value of the bifurcation point increases and greater stresses are required for the metal to lose its stability. However, very often a specified drawn cup thickness is required and application of a thicker sheet is not an option.

Further drawing produces a concentration of compression stress reaching 525MPa in creased flange bends (Figure 4c). Due to such large deformations of a flange, the resistance during the passing through the die-block rounded edge increases.

It brings about a rapid increase in the stamping force, which leads to thinning of the sheet metal on the rounded drawn cup edge.

Total wedging of the drawn cup inside the die block hole is shown in Figure 4d. Stresses in the flange folds exceed 615MPa. Further press forming could cause the bottom of the drawn cup to break or the tools to be damaged. It is dangerous to approach such a state, as it may prove impossible to remove the drawn cup due to elastic strains. However, numerical studies enable us to carry out such analyses and observe these phenomena.

### 6. Findings of numerical analysis with a blankholder

Although the blankholder force was 55% greater than the force calculated by the formula, its rising was observed at the initial stage (Figure 5a). Just the highest-pressure force was required in this moment, because the sheet metal edge was

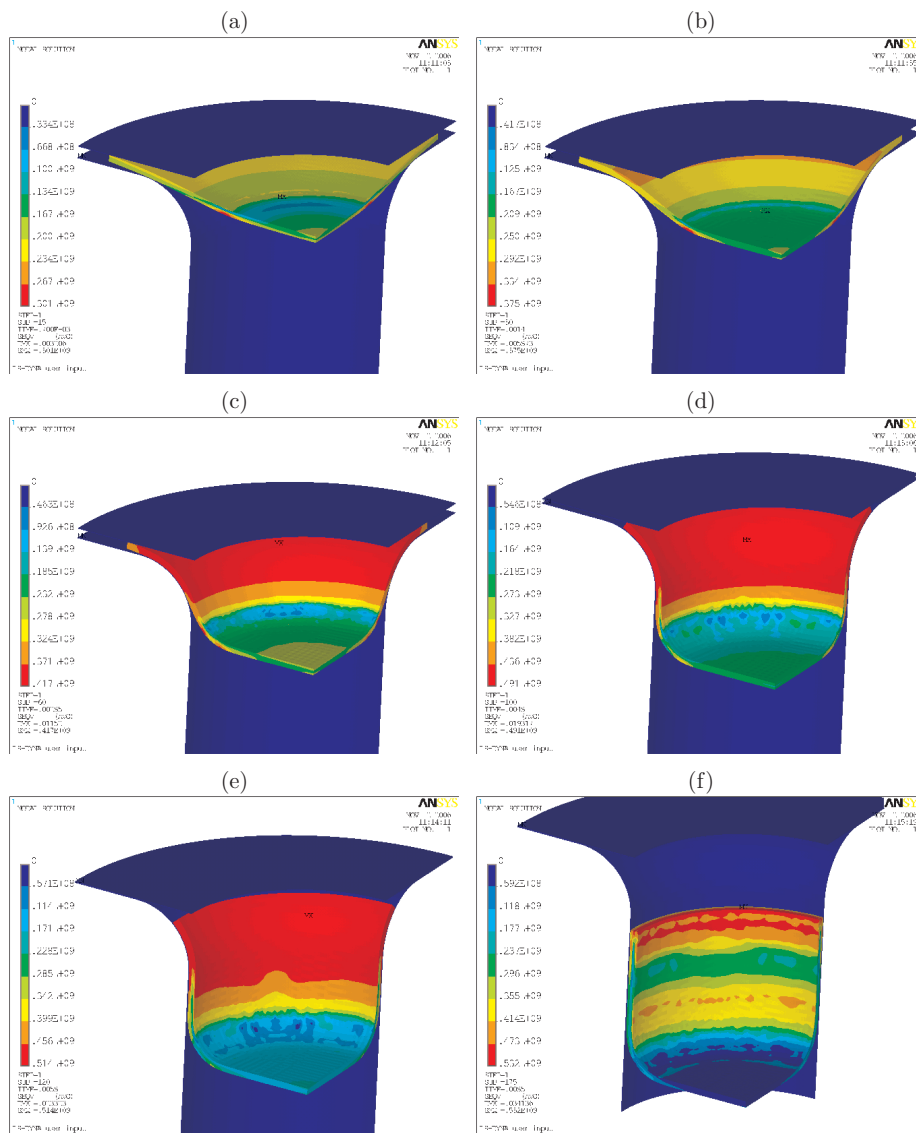


Figure 5. Findings of numerical analysis with a blankholder

situated at the maximum distance from the rounded die edge and the longest lever was produced.

At a further stage, when the pressure force was sufficient the sheet metal was bent on the die-block edge (Figure 5b) at the value of stresses equal to 334MPa. Raising the blankholder slightly at the initial stage is favorable to some extent, because the surface contact between the die block and the blankholder is reduced. A decrease in surface contact brings about a decrease in the sheet-metal friction; with lower friction, less force must be applied to the plunger die.

In the course of shifting the sheet metal inside the die block the blankholder holds it on the working surface (Figure 5c), thus preventing elastic buckling. In this case, a compressive circumferential stress of about 417MPa brings about a thickening of the sheet metal at the periphery. At this stage, the flange would have undergone a strong corrugation if not for the application of the blankholder.

When the sheet metal is passing through the die-block edge rounding (Figures 5d and 5e), the blankholder loses contact with the sheet metal. If the rounding of the die-block edge is too large, the contact is lost too early and the sheet metal may undergo corrugation. Therefore, application of smaller die-block edge roundings is recommended, so that the blankholder remains in contact with the sheet metal for the longest time possible.

At the final stage, only the drawn cup flange undergoes deformation (Figure 5f). The stresses amount to 532MPa and are limited to the inside of the product. Judging from the shape of the drawn cup and the range of stresses applied, one can determine whether the technological and model parameters were selected correctly.

## 7. Conclusions

Numerical analysis in the form of the finite element method, as used in the ANSYS LS-DYNA program, turned out to be extremely useful in solving the problem of sheet-metal corrugation. An experimental approach to this problem could be expensive and time-consuming, but it was solved by the central difference method, which did not require knowledge of the boundary conditions in the process. Despite sheet-plate forming being a slow process, it could be simulated using the dynamic method. Only the influence of the deformation velocity on the value of stresses was neglected.

It was found on the basis of two numerical analyses that the application of a blankholder was necessary given the assumed technological parameters. It was also observed that the greatest force of the blankholder was required at the beginning of the process. It should be decreased in the course of the process in order to reduce the force of friction between the sheet plate, the die block and the blankholder. A decrease in the friction force contributes to a decrease in the force required for sheet-plate forming.

The pressure force constant was applied in this analysis as a function of time. It was observed that the assumed value of  $P_{\text{doc}} = 500\text{N}$  was too small at the initial phase of the process when the blankholder was lifted.



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