Numerical Simulation of Rectangular Deep Draw Containers Made from Thin Molybdenum Sheet

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Abstract. The paper presents numerical simulation-FEM variations in the technological and design parameters of deformation at different levels during the plastic deformation of complexly shaped hollow parts of a pure molybdenum sheet in terms of the thermo forming. Variations of the process parameters such as deformation temperature, blank holder force, shape and geometry of the drawbeads, the shape and geometry of the blank thin sheet of the molybdenum metal allow making optimisation procedures for hot forming of the thin molybdenum sheet when the products of these processes have no rotational symmetry. The results of the numerical simulations in programming environments PAM-STAMP 2015 enable implementing the validation of each technological and design elements of the deformation system for an optimal process of plastic deformation of the rotationally asymmetrical hollow containers of the thin molybdenum metal as well as determining the critical deformation and stress zones in the discrete volumes of the molybdenum sheet metal. In the area of allowance, attention is to be paid to the shape and geometry of the drawbeads, friction ratios in the critical zones of deformation and to the aspect of their positive effect on the flow of molybdenum metal to unbalanced hole-forming tool to apply the criterion of the maximum allowable wall thinning yield.

1. Introduction

One of the features of the modern technology is the dramatic increase in demands for service characteristics of the material used. These materials include molybdenum sheet, used as a construction material working in conditions of heating at high temperatures. With reliable protection from oxidation the products made of molybdenum sheet have a sufficient stability of shape and size and a relatively high specific strength at high temperatures. Due to the mentioned quality parameters and due to the use of molybdenum sheet in the growth of optically transparent sapphire single crystals of refractory they are melted by the horizontal directional solidification - Horizontal directed crystallization (HDC) method [1].

The process of growing single crystals is characterised by the refractory critical values of the temperature and temperature gradient, reaching more than 2000°C. In these conditions the formation of the real structure of a sapphire single crystal is not completed and continues with their cooling. The HDC method is technically simple to create controlled temperature field necessary for growing a large...
single crystal weighing up to 80 kilos with desired optical properties. In this regard the form and the production technology of the crucibles are of a particular importance. The current design and manufacturing technology of containers is based on the bent molybdenum sheet using flame heating. This procedure has a number of disadvantages as to the formation of the desired crystallisation front and production of the high quality sapphire single crystal. The main disadvantages of the construction and existing technology manufacturing crucibles are as follows: when you move the crucible with the melt through a temperature gradient there is a distortion of the form of crystallisation front connected with a variable heat transfer between the melt and the crucible walls. The flame heating is an intense oxidation of the molybdenum sheet, which leads to the formation of cracks and leakages of the melt. However, it is difficult to work with the hot forming processes due to the extensive surface and edge cracking. Therefore, it is necessary to study the fracture behaviour of the pure molybdenum sheet and to establish the fracture condition to predict the crack initiation [2].

It is generally accepted that Finite Element Method (FEM) has been widely used as a tool to design a product and develop technological processes such as forming, induction hardening, machining, ECAP processes, etc. [3,4]. The main benefit of FEM is to shorten a time for a product to the market, to minimise a risk of die failure during a production, to reduce a number of trial-and-error in production and to reduce unnecessary down-time (maintenance) due to the uncertainty happening during productions [5]. FEM is being gradually adopted by industry to predict the formability of sheet metals. Sheet metal forming operation involves complex physical mechanisms that give rise to a high order non-linear problem [6]. A general nonlinear structural analysis can include the effects of large displacements, large strains and nonlinear material conditions [7,8]. FEM can provide not only the final results, but also the information of intermediate steps, like the distributions of displacement, stress, strain and other internal variables.

The objective of the presented work is to investigate the formability of the molybdenum sheet in deep drawing by FEM simulation, friction analyses, the effect of the process variables such as BHF, forming rate and blank diameter on the drawing depth, thickness distribution and positive or negative influence of drawbeads configuration on the molybdenum sheet plastic deformation.

The simulation is verified on a simple rotationally symmetric blank. Subsequently more complex containers using the same parameters are investigated. Here we monitor the influence of the container on the change of the technological and design properties with the goal to find the best suitable parameters. Wang et al. deals in work [9] with the influence of the thermal deep drawing on the analysis of the pure molybdenum sheet for the axially symmetric yields and this work will be compared just with these results. The deep drawing process is affected by a large number of factors and friction belongs to the most important ones. Meng et al. [10] deals with the influence of the pure molybdenum sheet friction during the deep drawing process at an elevated temperature. The results show that an increasing forming temperature of the Mo sheets leads to a reduced drawing force and an increased friction coefficient. Therefore it is effective to use a lubricant for improving the Mo sheets’ formability.

2. Molybdenum
Molybdenum is the lightest available heat-resistant material. It is typical by its excellent strength properties at increased temperatures, high resistance against corrosion except for the resistance against oxidation at a temperature higher than 973K, with high thermal conductivity, high flexibility module and a low coefficient of the thermal expansion [2]. The low formability of molybdenum significantly affects its utilisation. However, the formability of the Mo sheets can be improved by increasing the forming temperature before or during the forming process. Heat forming is an effective technology for manufacturing the Mo thin-wall components which also brings better friction properties between the sheets and tools [10].

We can observe that the tensile strength and the yield point of molybdenum at the room temperature is 980MPa and 690MPa with an extension of 8%, which shows its bad plastic properties at the room temperature, see the figure 1.
Based on the experimental measurements of the single-axis tensile tests we can observe the influence of deformation and temperature on the deformation strengthening. The deformation strengthening declines with the increasing temperature and decreasing strain rate (figure 2). The dynamic softening of the behaviour can be seen when the temperature is 1093K and higher, when the strain hardening predominates at a temperature lower than 1093K [11].

3. Used material model

Due to a better operation of the programme PAM-STAMP it is more suitable to use the material model or to approximate the curve acquired during the tensile strength test up to the value of true strain 1 than to use the discrete values in dependence on the true stress-true strain. [12] The tensile tests were realised at various temperatures (993K, 1043K, 1093K and 1143K) Because of the high molybdenum sheet oxidation at increased temperatures the test samples were sprayed by the anti-oxidant coating. This coating did not affect the strength properties. The tests were realised on a universal test machine Yonekura. Several material models were created from the experimental results of the tensile tests (figure 3). The Hollomon’s equation describes strain hardening as a power law function of stress and strain after yielding

\[ \sigma = k \varepsilon^n \]  

(1)

where \( k \) and \( n \) are material constants known as the strength coefficient and the coefficient of deformation strengthening. The constants \( k \) and \( n \) are acquired from the curves of dependence of the true stress on true strain by calculating the logarithm of both equation sides

\[ \ln \sigma = n \ln \varepsilon + \ln k \]  

(2)

\[ Y = A(x) + B \]  

(3)

This equation is an equation of the straight line whose inclination is \( n \) and whose intersection point with the axis y is \( \ln k \). [13]
4. Friction Coefficient

The friction coefficient it is a very important factor affecting the deep drawing process. At present there is not at disposal any generally accepted method of determining the friction coefficient under plastic deformation of the thin sheets. The particularity of the presented determination method of the friction coefficient lies in the fact that the indicator is the sample of the tested sheet itself [14]. The investigation of Thiébaut et al. [15] also deals with the friction coefficient of molybdenum and his work shows that the coefficient value grows with the increasing temperature. For the Tresca law it says the friction coefficient is $f = 55.4/(1353-T)$ and for the Coulomb law $g = 23.8/(1332-T)$. For the temperature $T = 1023K$ we obtain $f = 0.17$ and $g = 0.08$. The friction coefficient between the steel tool and molybdenum sheet used for this work was achieved by an experimental tool (figure 5) and its value was stated as $f = 0.21$.

The calculation of the friction coefficient results from the equilibration conditions of the forces and moments acting on the tested element of a unit width.

$$\sum F_x = \sigma \cdot s^* - \sigma \cdot s \cdot \cos \alpha + F_t \cos \alpha_0 - F_N \sin \alpha_0 = 0$$  \hfill (4)

$$\sum F_y = \sigma \cdot s \cdot \sin \alpha - F_t \sin \alpha_0 - F_N \cos \alpha_0 = 0$$  \hfill (5)

$$\sum M_0 = \sigma \cdot s^* - \sigma \cdot s + F_t = 0$$  \hfill (6)
where \( s', s'' \) are elements of thickness in the end parts in a deformed condition,

\[ F_N \] - a normal force component by which the tool acts on the sample element,
\[ F_t \] - the friction force,
\( A \) - the half angle,
\( \alpha_0 \) - the angle between y axis and force of normal components \( F_N \),
\( \sigma \) - normal stresses, determined from the tensile test diagram.

The actual deformations were determined from the equations:

\[ \varepsilon' = \ln \frac{s_0}{s'} ; \quad \varepsilon'' = \ln \frac{s_0}{s''} \]  \( (7) \)

where \( s_0 \) – the initial sample thickness. After adjusting we determine the force \( F_t \) from the following equation

\[ F_t = \left( \sigma s' \sin \alpha - F_N \right) \frac{\cos \alpha_0}{\sin \alpha_0} \]  \( (8) \)

Then we determine the friction coefficient under the sheet plastic deformation from the equation

\[ f = \frac{F_t}{F_N} \]  \( (9) \)

5. Deep drawing of cylindrical cup
The simulation was dealing with the correctness of the material model, the friction coefficient and marginal conditions in the programme PAM-STAMP 2015 and with comparing the results with the experimental results of the Beihang University [10]. The scheme of the tools and their geometry is shown in the figure 7. One plane of symmetry was used (figure 8).

Due to the low formability of the Mo sheet at the room temperature the experiments were carried out at an elevated temperature and the sheets were prevented from oxidation with an anti-oxidation coating. The thickness of the pure Mo sheet is 0.5 mm. The simulations were carried out at several temperatures and the optimal temperature is 1123K. A blank with diameter of 95 mm and temperature of 1023K can be taken as an example. The blank holder force (BHF) varies from 12kN to 2kN and the results show that wrinkling occurred on the blank at the BHF of 2kN and fractures occurred on the blank at the BHF of 2 and 12 kN, while the blank under the BHF from 4 to 10 kN can be successfully deep drawn. Thus, the reasonable range for BHF in the thermal deep drawing simulation can be assumed from 4 to 10kN [10] and the simulation results are presented in the figures 9 and 10.
Figure 9. The course of thinning at BHF 2kN.

Figure 10. A successfully deep drawn cup.

All these experiments were realised as a FE simulation and in this way the correct marginal conditions in the PAM-STAMP were verified. The Hill 48 was used as the plasticity model. The thinning method was used as a criterion for assessing the yield. The maximal thinning of 0.14 was considered for the given material.

6. Deep drawing of the rectangular container

The simulation of an angular yield with the same marginal conditions used for the simulation of the axisymmetric containers with a temperature of 1023K was carried out. The various shapes and geometry of the drawbeads was used and we also monitored their influence on the thinning of the rectangular parts. The shapes of the drawbeads are shown in the figure 11 and we varied the dimensions for each rib. The drawbeads were placed to those areas where the material has to be decelerated as much as possible. The figures 12 and 13 show the geometry and due to saving the computer capacity only two symmetry levels were used. The blank in the simulation had dimensions of 160 x 160 mm.

Figure 11. The various shapes of the drawbeads

The figure 14 shows the result without using a drawbead – the maximal achieved depth of the yield was 36 mm. The subsequent implementation of the drawbead for all types resulted in increasing the thinning. Only in the case of the type a there developed a reduction of the thinning and in this way the depth of the yield was increased by a value of 3 mm – see the figure 15 for $R_1=2.0$, $R_2=2.0$, $D=2.0$ and $G=1.3$. We note that the results presented in this paper are supported by experimental tests of the cylindrical container with a diameter of 80 mm at a temperature of 20°C (figure 16). This creates real assumptions for mathematical simulations of the optimal deformation conditions for forming crystallisation containers from molybdenum sheet for the sapphire monocrystal which is realised by the horizontal method of crystallisation according to Bagdasarov (figure 17).
Figure 12. A model of the forming system.

Figure 13. The geometry of the forming system and placement of the drawbeads.

Figure 14. The rectangular container without using the drawbeads.

Figure 15. The rectangular container with using the drawbeads of the a type.

Figure 16. Molybdenum cylindrical containers.

Figure 17. FEM implementation of the crystallisation container - HDC method.
7. Conclusion
The results of the simulation of the rotational symmetric container show that the selected boundary conditions appropriately describe the really measured values. A model of the rectangular container was created by using the same boundary conditions. The maximal depth of the yield acquired from the given blank was 36 mm. The objective of the simulation was to increase the maximal depth of the rectangular container without any damage by using the drawbeads. The simulation results show decrease in ductility due to increasing the value of the rectangular container thinning. Only when we used the rib shape a reduction of the thinning developed and in this way the depth of the rectangular container was extended by a value of 3 mm. This simulation can serve for the future design of the forming system which will already consider only the selected shapes of the drawbeads and this will result in achieving significant economic savings of a new design. Another important factor detected during simulations is that the friction coefficient fundamentally affects the deformation process of the Mo sheet and due to this fact it is necessary to influence its maximal reduction during the real experimental analyses.

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