THE FORCE OF DEEP DRAWING

Branko Grizelj[1,*], Marija Stoić[2], Irena Jukić[3], Miroslav Duspara[1], Dejan Marić[1]

[1]Strojarski fakultet u Slavonskom Brodu, Sveučilište J.J. Strossmayera u Osijeku, Slavonski Brod, Hrvatska
[2] VUSB, Slavonski Brod, Hrvatska
[3] KREIRE Metal, Slav. Brod, Hrvatska

[*]Autor za korespodenciju. E-mail: bgrizelj@sfsb.hr

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Abstract:

The term metal forming refers to a group of manufacturing methods by which the given shape of a workpiece (a solid body) is converted to another shape without change in the mass or composition of the material of the workpiece. In this paper, the basics of a deep drawing process for the production of a thick plate steam boiler end caps are shown. Also the analysis of stresses which appear in the deep drawing process are shown – bending stress, frictional stress and inner stress due to displacement of material are also shown. Afterwards some mathematical formulations are made in order to find total stresses which appear in the material during the forming process which are needed for the force calculation.

1 INTRODUCTION

The term metal forming refers to a group of manufacturing methods by which the given shape of a workpiece (a solid body) is converted to another shape without change in the mass or composition of the material of the workpiece. The manufacturing processes are divided into six main groups.

1. Primary forming = Original creation of a shape from the molten or gaseous state or from solid particles of undefined shape, that preserves cohesion between particles of the material. 2. Deforming (Metal forming). 3. Separating = Machining or removal of material, that destroys cohesion. 4. Joining = Uniting of individual workpieces to form subassemblies by filling and impregnating of workpieces, and so on, that increases cohesion between several workpieces. 5. Coating = Application of thin layers to a workpiece, for example, galvanizing, painting, coating with plastic foils, that creates cohesion between substrate and coating. 6. Changing the material properties = deliberately changing the properties of the workpiece in order to achieve optimum characteristics

at a particular point in the manufacturing process. These methods include changing the orientation of micro-particles as well as their introduction and removal, such as by diffusion, that rearranges, adds, or removes particles. Classification of metal-forming methods by subgroups [1-4] is shown at Figure 1.

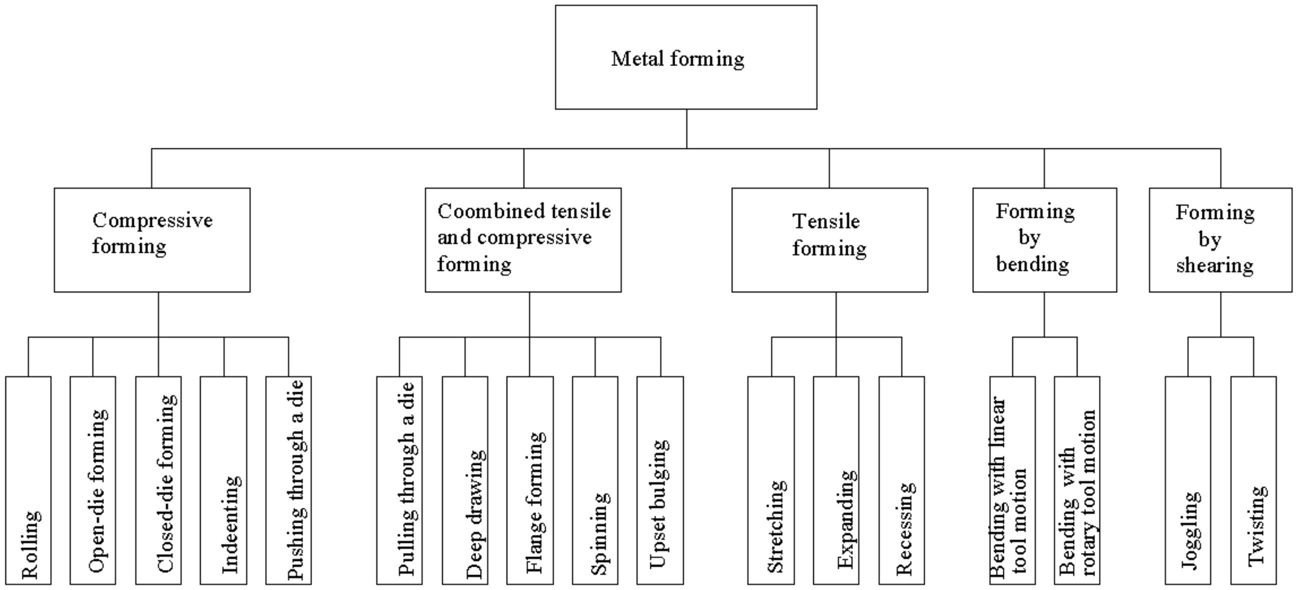
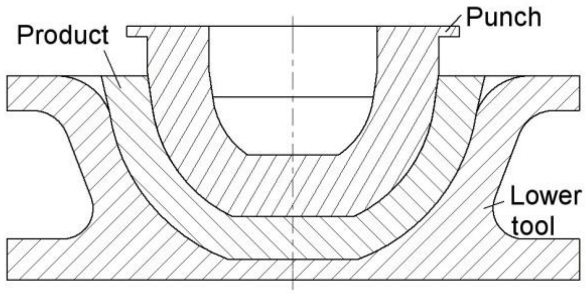


Figure 1. Classification of metal forming methods by subgroups.[1-4]

The production of thick plate steam boiler end caps is usually performed in one or more work travels on hydraulic presses. The designer of hydraulic presses and the engineer responsible for deep drawing of products should be aware of the amount of deep drawing force in the process.

So far, the empirical and theoretical expressions have shown to have very different results. In order to examine deep drawing forces which appear in the deep drawing process, a tool shown in Figure 2. and Figure 3. was used.



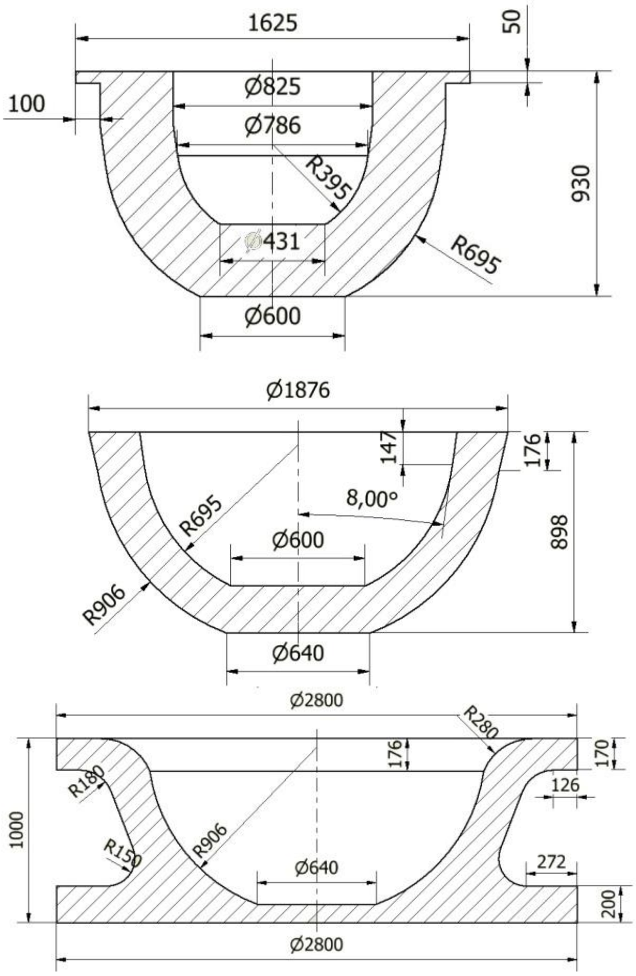


Figure 2. Experimental tool geometry and dimensions.

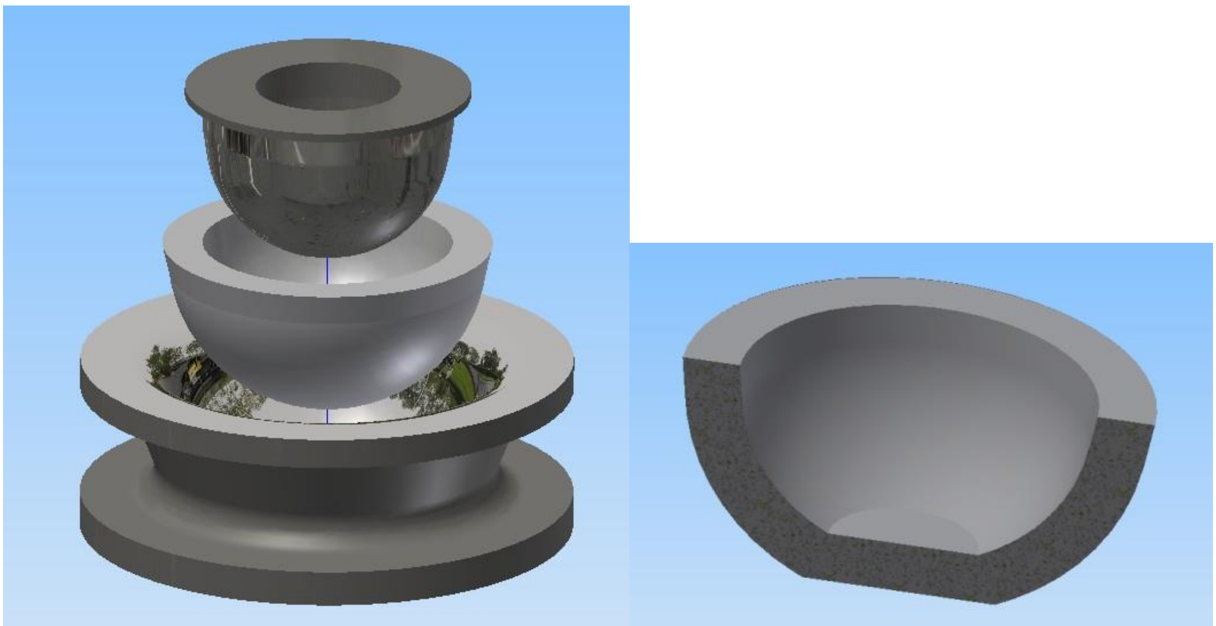


Figure3. 3D model of experimental tool and deep drawn product.

Deep drawing process is performed in such a way that first a thick metal plate (dimensions 2180 mm in diameter and 210 mm thick) is heated-up to forming temperature, and then it is formed with tools under the pressure of hydraulic press.

2 FORCE CALCULATION

Plasticity is the capacity of a material to change its shape permanently under the action of forces when the corresponding stress state reaches a material-dependent critical magnitude called yield strength or initial flow stress. As seen from the results of the tension test, when the stress is below the yield strength, the deformation disappears upon unloading: the material behaves elastically. If the stress exceeds the yield strength, permanent deformation results. Upon unloading, the workpiece has a form that is different from its initial one. It is then said to have been plastically or permanently deformed, or, if a definite final shape was sought, it has been transformed. Materials which behave in an elastic-plastic manner can, after having been permanently deformed, again be loaded until the flow stress is reached (it now has a magnitude larger than the initial one) without additional permanent deformation setting in. This increase in the flow stress as a result of prior deformation is called strain hardening. The aim of the theory of plasticity is on theoretical grounds to obtain information on stress and movement condition that prevail in a workpiece during a forming process. This demand has led to a – as confirmed by experiments – true (albeit simplified) description of the physical processes in miniature, je out of the element.

In the design of tools for metal forming processes we will try to determine the magnitude of the deformation zone. These are primarily dependent on the properties of the workpiece, material state of the friction conditions in the active joint and on the tool design. Useful statements about power and labor requirements of a forming process for the selection of the forming machine, and the optimum design of the tools could be made by simplistic assumptions with the methods of the elementary theory of plasticity. The recent developments in the higher plasticity theory methods allow accurate calculations. The basis of these calculation methods is as accurate as possible knowledge of the forming of metals.

In order to obtain the forming force needed for deep drawing process, it is necessary to understand which stresses act on infinitively small element which is shown in Figure 4. and Figure 5.

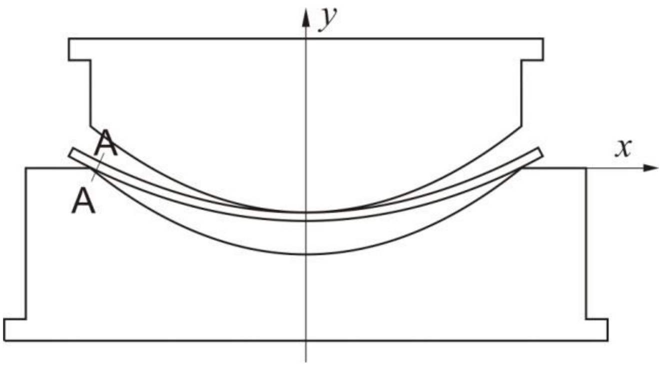


Figure 4. Schematic illustration of bending of plate with marked A-A section [1,4].

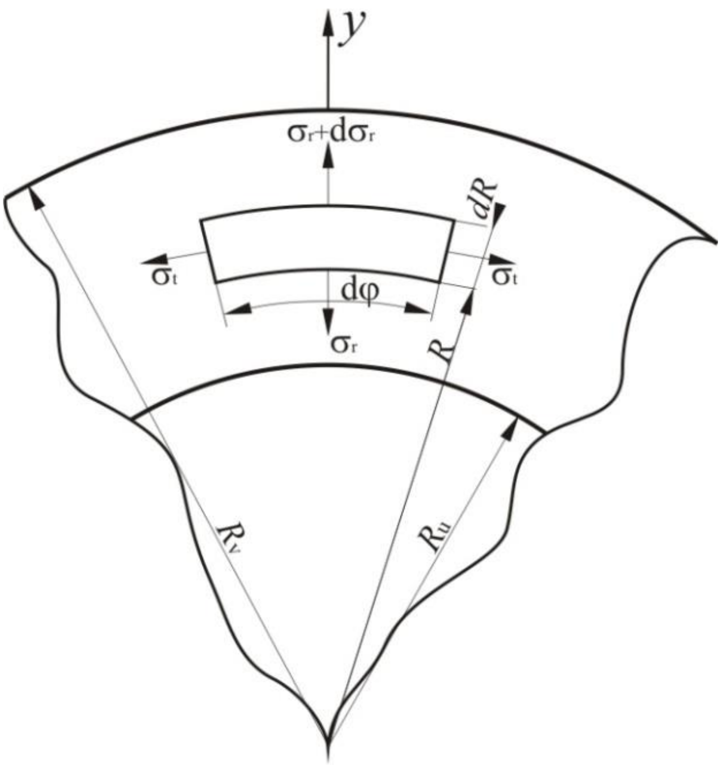


Figure 5. Stresses which act in marked section A-A form Figure 3. [1]

From Figure 3. it can be seen that section A-A is important for understanding stresses which act on the infinitive small element. This stresses are: plastic deformation stress σ_{u}, stress form friction over the edge σ_{fr} and bending stress σ_{bend} [1].

Total stress is calculated as:

$$\sigma_{tot} = \sigma_{u} + \sigma_{fr} + \sigma_{bend} \tag{1}$$

In order to obtain stress of plastic deformation σ_{u} it is necessary to use infinitesimally small element and forces acting on it which can be seen if Figure 4 [1].

From the condition that all forces in *y* direction are in equilibrium it can be written that [1,4]:

$$\left(\sigma_r + \sigma_t\right) dR + d\sigma_r \cdot R = 0 \tag{2}$$

In order to solve this differential equation (2) one additional expression must be introduced where k_f is forming stress:

$$k_f = \sigma_r + \sigma_t \tag{3}$$

After combining expressions (3) and (4) the solution of differential equation can be found as [1]:

$$\sigma_u = k_f \cdot \ln\left(\frac{R_v}{R_u}\right) \tag{4}$$

During the forming process, a plate is moving over the filleted edge with respective radius r_M and this plate needs to overcome the force of friction. This results in the larger stress near inner radius R_u which consists from bending and friction stresses.

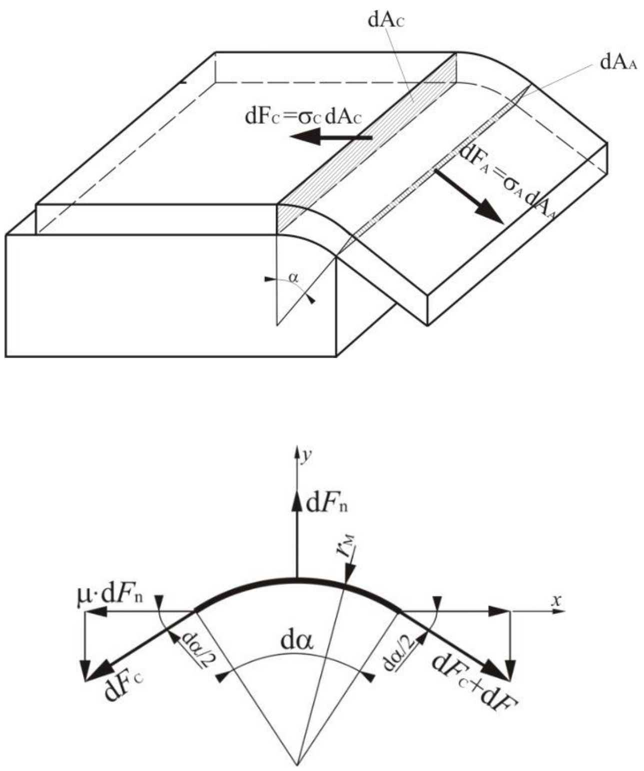


Figure 6. Schematic illustration of a plate moving over filleted edge of the tool and forces acting on the infinitesimally small element. [2]

If force dF_A increases for amount $dF=dF_A-dF_C$ there will be movement of sheet metal. By increasing the bending detail it can be shown that the forces which act on the bended surface looks like in Figure 6. Elementary band shown in Figure 5. has length $dl=r_M \cdot d\alpha$ [2].

From Figure 6., if all forces are set to be in equilibrium, and their values projected on *x*, and *y* axis, two equations can be written.

$$\sum X = 0$$
$$\left(dF_{\mathrm{C}} + dF\right) \cdot \cos\frac{1}{2}d\alpha - dF_{\mathrm{C}}\cos\frac{1}{2}d\alpha - \mu dF_{\mathrm{N}} = 0 \tag{5}$$

$$\sum Y = 0$$
$$dF_{\mathrm{N}} - \left(dF_{\mathrm{C}} + dF\right)\sin\frac{1}{2}d\alpha - dF_{\mathrm{C}}\sin\frac{1}{2}d\alpha = 0 \tag{6}$$

Expressions (5) and (6) can be written as:

$$dF - \mu dF_{\mathrm{N}} = 0 \tag{7}$$

$$dF_{\mathrm{N}} - dF_{\mathrm{C}} \cdot d\alpha = 0 \tag{8}$$

When this two equations are combined it follows that:

$$dF = \mu dF_{\mathrm{C}} \cdot d\alpha \tag{9}$$

$$\Delta F = dF_{\mathrm{A}} - dF_{\mathrm{C}} = dF_{\mathrm{C}}\left(e^{\mu\alpha} - 1\right) \tag{10}$$

Then it can be written that

$$\sigma_{\mathrm{fr}} = \frac{\Delta F}{\Delta A},\ \mathrm{MPa}$$
$$\sigma_{\mathrm{fr}} = \sigma_{\mathrm{u}}\left(e^{\mu\alpha} - 1\right),\ \mathrm{MPa} \tag{11}$$
$$\sigma_{\mathrm{fr}} = k_f \cdot \ln\left(\frac{R_{\mathrm{v}}}{R_{\mathrm{u}}}\right)\left(e^{\mu\alpha} - 1\right),\ \mathrm{MPa}$$

Bending stresses in the steam boiler cap will be positive in the outer tensile zone, and negative in the inner compressive zone in front of neutral plane.

This stress will increase with the thickness of the plate, and it will decrease with larger radius r_{M}.

Bending stress can be calculated with the following expression [2]

$$\sigma_{\mathrm{bend}} = k_f \cdot \frac{s}{4r_{\mathrm{M}}},\ \mathrm{MPa} \tag{12}$$

This, combined with the expressions (1,5,12) leads to the following expression used for the calculation of total stresses in the material during forming [2]:

$$\sigma_{\mathrm{tot}} = k_f \left(\ln\left(\frac{R_{\mathrm{v}}}{R_{\mathrm{u}}}\right) \cdot e^{\mu\alpha} + \frac{s}{4r_{\mathrm{M}}} \right), \ \mathrm{MPa} \tag{13}$$

Since total stresses are known, the forming force can be calculated with the following expression:

$$F_{\mathrm{tot}} = A_{\mathrm{A}} \cdot \sigma_{\mathrm{uk}}, \ \mathrm{N}$$

$$F_{\mathrm{tot}} = 2 \cdot R_{\mathrm{v}} \cdot \pi \cdot s \cdot k_{\mathrm{f}} \left(\ln\left(\frac{R_{\mathrm{v}}}{R_{\mathrm{u}}}\right) \cdot e^{\mu\alpha} + \frac{s}{4 \cdot r_{\mathrm{M}}} \right) \tag{14}$$

There are several more expressions with which the forming force can be calculated and for the purposes of this work only two of them will be mentioned.

The expression for calculation of forming force according to Dinom [3]:

$$F_{\mathrm{tot}} = 2 \cdot R_{\mathrm{u}} \cdot \pi \cdot s \cdot R_{\mathrm{m}} \left(\frac{R_{\mathrm{v}}}{R_{\mathrm{u}}} - b \right), \ \mathrm{N}$$

$$b = 0,6 \ \rightarrow \ \text{coefficient} \tag{15}$$

And the expression for the calculation of forming force according to Tomlenov [3]:

$$F_{\mathrm{tot}} = (1,5 \div 2) R_{\mathrm{m}} \cdot \ln\left(\frac{R_{\mathrm{v}}}{R_{\mathrm{u}}}\right) \cdot \pi \cdot R_{\mathrm{u}} \cdot s, \ \mathrm{N} \tag{16}$$

According to Siebel’s expression, the forming force can be calculated as [3]:

$$F_{uk} = 1,3 \cdot \pi \cdot R_v \cdot s \cdot R_m \cdot \ln\left(\frac{R_v}{R_u}\right), \ \mathrm{N} \tag{17}$$

3 EXPERIMENT

For the experiment, a steel plate of D_0 2180 mm in diameter and *s* 210 mm of thickness was used. During the forming plate was coated with graphite mixed with mineral oil. The temperature of heating of a steel plate was 1100°C and by the time the steel plate was mounted on the tool the temperature has dropped to 1040°C.

At the end of the forming process the temperature of the steel plate was 920°C.

The time needed for the plate to be extracted from the furnace and until the end of the forming process was 10-13 minutes. The forming process was performed in the 50 MN forming hydraulic press. In the production a 23 steam boiler caps were made, and maximal forming force was 28,6 MN.

Maximal difference of forming force in the production of 23 boiler caps was 2 MN.

Since material was heated to the medium temperature of R_m (k_f) 970°C, the forming stress and the tensile stress were assessed to 76 MPa according to the manufacturer data.

With the above mentioned data, and the use of Figure 1 (from which R_u = 695 mm, R_v = 906 mm), the forming force F_{tot} can be calculated.

From (14):

$$F_{tot} = 2 \cdot 906 \cdot \pi \cdot 210 \cdot 76 \left(\ln\left(\frac{906}{695}\right) \cdot e^{0,2 \cdot 1,57} + \frac{210}{4 \cdot 280} \right)$$

$$F_{tot} = 50022389 \ \text{N} \approx 50 \ \text{MN}$$

From (15):

$$F_{tot} = 2 \cdot 695 \cdot \pi \cdot 210 \cdot 76 \left(\frac{906}{695} - 0,6 \right) = 49037842 \ \text{N}$$

$$F_{tot} \approx 49 \ \text{MN}$$

From (16):

$$F_{tot} = 2 \cdot 76 \cdot \ln\left(\frac{906}{695}\right) \cdot \pi \cdot 695 \cdot 210 = 18477886 \ \text{N}$$

$$F_{tot} \approx 18,5 \ \text{MN}$$

From (17):

$$F_{tot} = 1{,}3 \cdot \pi \cdot 2 \cdot 906 \cdot 210 \cdot 76 \cdot \ln\left(\frac{906}{695}\right) = 31314033 \text{ N}$$

$$F_{tot} \approx 31{,}3 \text{ MN}$$

4 CONCLUSION

Deep drawing is one of the most important processes for sheet-metal forming. It is the base for the mass production of part pieces for many different applications, such as lighter casings or parts of automobile bodies. Deep drawing DIN 8584 may be defined as follows: deep drawing is a process in which a blank or workpiece, usually controlled by a pressure plate, is forced into and/or through a die by means of a punch to form a hollow component in which the thickness is substantially the same as that of the original material.

In this paper the basics of a deep drawing process for the production of a thick plate steam boiler end caps are shown. Theoretical analysis of stresses which appear in the deep drawing process are shown – bending stress, frictional stress and inner stress due to displacement of material are shown.

These stresses are described, and some mathematical formulations are made in order to find total stresses which appear in the material during the forming process.

Later the expression for the calculation of the forming force is shown. Also some other experimental formulations from the literature are presented.

These expressions were used for the calculation of the deep drawing force, and later the results were compared to the experimentally obtained force values in the production of boiler end caps.

The results show that the closest amount of force can be calculated with the expression (17). The difference in the results is from large amount of assumptions and simplifications used in the formulation.

Also some other forces exists in the forming process, and stresses which are caused by this forces needs to be further investigated by FEM methods in order to better understand the deep drawing process.

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