Journal of Mechanics Engineering and Automation 4 (2014) 804-812

# Design, Fabrication and Experimentation of a Deep Drawing Machine

Ahmed Ramahi and Yahya Saleh

*Department of Industrial Engineering, Faculty of Engineering, An-Najah National University, Nablus P.O. Box 7, Palestine*

Received: August 23, 2012 / Accepted: September 14, 2012 / Published: October 25, 2014.

**Abstract:** This paper presents the work implemented in designing, fabricating and operating a model of a cheap hydraulic DDM (deep drawing machine), which is currently utilized in the manufacturing processes lab in the IED (Industrial Engineering Department) at An-Najah National University. The machine is used to conduct different experiments related to the deep drawing process. This work was implemented in three stages: the first was the design stage, in which all design calculations of the DDM elements were completed based on the specifications of the product (cup) to be drawn; the second was the construction stage, in which the DDM elements were fabricated and assembled at the engineering workshops of the university; the last was the operating and experimentation stage, in which the DDM was tested by conducting different experiments. The experience gained from designing and constructing such a mechanical lab equipment was found to be successful in terms of obtaining practical results that agree with those available in literature, cost-effective relative to the cost of a similar purchased equipment, as well as enhancing students' abilities in understanding the deep drawing process in particular and machine elements design concepts in general.

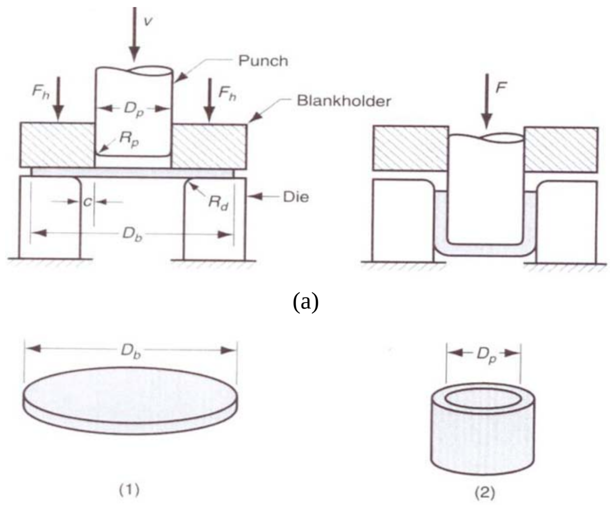
**Key words:** Deep drawing, machine element design, die design, machine assembly and fabrication, experimental investigation of draw force and draw stroke.

## 1. Introduction

Deep drawing is a sheet-metal working process used to form cup-shaped or box-shaped parts by using a punch that draws a blank into a die cavity. This process is carried out by placing a blank sheet of certain size over the opening of the die and pressing this blank into the die cavity with a punch, as illustrated in Fig. 1 [1, 5].

Typical products made by this process are beverage cans, bathtubs, containers of different sizes and shapes, sinks and automobile panels. In this work, the basic drawing operation is studied, which is the drawing of a cup-shaped part with parameters as shown in Fig. 1. In this basic operation, a circular blank sheet of a diameter $D_b$ and a thickness $t$ is placed over the die opening of a die having a corner radius $R_d$. Then the blank is held by a blank holder (hold-down ring) with certain force. After that, a punch of a diameter $D_p$ and a corner radius of $R_p$ is used to punch the blank sheet into the die cavity, thus forming the cup-shaped part. In addition, the punch moves at a certain velocity $V$ and applies a certain downward force $F$ to achieve the deformation of the metal, while the blank holder applies holding force $F_h$ to prevent blank wrinkling [10, 11]. This paper presents the design and fabrication of a cheap DDM (deep drawing machine) that produces a pre-identified cup-shaped product. The DDM is now mounted and used for experimentation in the Manufacturing Processes Lab in the IED (Industrial Engineering Department) at An-Najah National University. We present the detailed design of the DDM main elements including the punch and the die, and the fabrication and assembly of the DDM. Also, we present the operation and testing of the DDM through conducting experiments on drawing force versus drawing stroke and comparing the results with published data. The paper is organized as follows: Section 2 presents a general background of the deep drawing process;

**Corresponding author:** Yahya Saleh, assistant professor, research field: manufacturing and service systems. E-mail: ysaleh@najah.edu.




(b)

**Fig. 1 (a) Drawing of a cup-shaped part: start of operation before punch contacts work and near end of stroke; (b) corresponding work part: starting blank and drawn part (*C* = clearance, $D_b$ = blank diameter, $D_p$ = punch diameter, $R_d$ = die corner radius, $R_p$ = punch corner radius, *F* = drawing force, $F_h$ = holding force).**

Section 3 includes the cup specifications, drawing and holding force caculations; Section 4 gives the design details of the DDM; while Section 5 presents those related to its fabrication and assembly; Section 6 includes the operation and experimentation of the machine; and Section 7 concludes our work.

## 2. Deep Drawing Process: General Background

This section discusses some general concepts of the deep drawing process including the drawing measures, drawing force and holding force.

### *2.1 Deep Drawing Measures*

One of the most important measures of deep drawing operation is the LDR (limiting drawing ratio), which is defined as the maximum ratio of blank sheet diameter to punch diameter that can be drawn under ideal conditions in one stroke without failure [9]. More specifically,

$$LDR = \frac{D_{b\max}}{D_P} \quad (1)$$

An approximate upper limit on *LDR* is a value of 2.

Another measure of drawing is the *Re* (reduction), which is defined as

$$Re = \frac{D_b}{D_b} - \frac{D_p}{D_b} = 1 - \frac{1}{LDR} \quad (2)$$

The reduction is closely related to *LDR* and its value should be less than 0.5. A third measure of deep drawing operation is the thickness to diameter ratio ($t/D_b$), which is often expressed as a percent. It is preferable that $t/D_b$ ratio is to be greater than 1%. As $t/D_b$ decreases, the tendency for wrinkling increases [1]. Furthermore, the punch-to-die clearance is usually some 10% larger than the sheet thickness to accommodate blank thickening during the drawing process [2]. Thus, the clearance (*C*) can be expressed as

$$C = 1.1t \quad (3)$$

### *2.2 The Drawing Force*

The force in the punch required to produce a cup is the summation of the ideal deformation force, the frictional forces and the force required to produce ironing. Fig. 2 shows the relation between the draw force and the draw stroke [2]. Eq. (4) has been developed to approximate the total punch force to deep draw a blank of $D_b$, at any stage in the process [3].

$$F = \left[\pi * D_p * t\ (1.1\ \sigma_{avg.}) * \ln\left(\frac{D_b}{D_p}\right) + \mu\left(2 * F_h\left(\frac{D_b}{D_p}\right)\right)\right] * \exp\left(\mu * \left(\frac{\pi}{2}\right)\right) + B \quad (4)$$

where, $F$ = total punch force, $\sigma_{avg.}$ = the average flow stress, $d$ = punch diameter, $D$ = blank diameter, $F_h$ = blank holding force, $B$ = force required for bending and unbending blank, $t$ = wall-thickness and $\mu$ = coefficient of the friction.

However, Eq. (4) is somewhat difficult to deal with because many variables are involved in the operation and deep drawing is not a steady state process. Hence, an approximate equation of the maximum punch force ($F$) has been developed as [2]:

$$F = \pi D_b\, t\, (UTS)\left(\frac{D_b}{D_p} - 0.7\right) \quad (5)$$

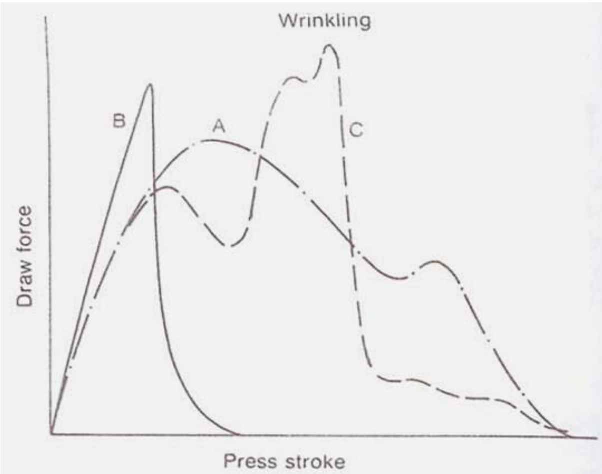



**Fig. 2 Punch force vs. punch stroke for deep drawing. Curve A typical of drawing with optimum blank holder pressure.**

where, $F$ = maximum drawing force, in *lb* (N), $t$ = original blank thickness (mm), *UTS* = ultimate tensile strength, $lb/in^2$ (MPa), and $D_b$, $D_p$ = the starting blank diameter and punch diameter (mm), respectively. The drawing force $F$ varies throughout the downward movement of the punch, usually reaching its maximum value at about one-third the length of the punch stroke [1].

*2.3 Blank Holding Force*

The holding force $F_h$ plays an important role in the deep drawing. As a rough approximation, the holding pressure can be set at value equals 0.015 of the yield strength of the sheet metal [1]. Thus, by multiplying the holding pressure by the portion of the starting area of the blank which is to be held by the blank holder, we can estimate the holding force $F_h$ as [1]:

$$F_h = 0.015 S_y \pi \left[ D_b^{\,2} - (D_p + 2.2t + 2R_d)^2 \right] \tag{6}$$

where, $F_h$ = maximum holding force in deep drawing, in *lb* (N), $S_y$ = yield strength of the sheet metal, $lb/in^2$ (MPa), and $R_d$ = die corner radius (mm).

*2.4 Tooling and Equipment*

A double-action mechanical press is generally used for deep drawing, hydraulic presses are also used. The double action press controls the punch and blank holder independently and forms the part at a constant speed. Since blank holder force controls the flow of the sheet metal within the die, new presses have been designed with variable blank holder force. In those presses, the blank holder force varies with punch stroke. The most important factor in the die design is the corner radius ($R_d$) of the die. This radius must have an optimal value since the material is pulled over it. The value for the optimal radius of the die depends upon the print requirement and the type of the material being drawn. Obviously, the smaller the die radius, the grater the force needed to draw the cup. The radius of the die may be between four to eight times the thicknesses of the blank [3, 8]. That is:

$$4t \le R_d \le 8t \tag{7}$$

Practically, it is recommended to start with $R_d$ equal $4t$ and increase it if necessary. Similarly, the punch nose radius ($R_p$) is important since it shapes the radius of the bottom of produced cup. If $R_p$ is too small, the bottom radius of the cup may tear out. It may be necessary to make the radius larger than needed, and reduce its size in subsequent drawing operations. As a start, a $4t$ radius-to-blank thickness may be used [3].

## 3. Cup Specifications, Drawing and Holding Force Calculations

The DDM was designed to produce cup-shaped parts in a single stroke. As stated earlier, the purpose of designing the DDM is to provide the manufacturing processes lab at An-Najah National University with an apparatus that demonstrates the deep drawing process and also to be used by students to perform some basic experiments related to the deep drawing process. In order to design a proper DDM, it is necessary to determine the product (the cup) specifications, drawing force and holding force at first.

*3.1 Cup Specifications*

The product of the required DDM is chosen to be a simple cup having a certain inner diameter (*d*) and depth (*h*) and to be produced using a sheet metal of thickness (*t*). The dimensions of the cup must be selected such that the deep drawing operation is feasible to produce the cup in single stroke. To measure the feasibility of the operation, the *LDR*, *t*/*D* (thickness-to-diameter) ratio and the reduction (*Re*) percentage must satisfy the feasibility conditions mentioned previously. To this end, it was decided that the thickness of the sheet metal to be used in producing the cup is $t$ = 1/32 in. = 0.8 mm, and, hence the corresponding die radius is $R_d$ = 1/8 in. = 3.2 mm, punch radius is $R_p = 4t$ = 4/32 = 1/8 in. = 3.2 mm, and the clearance (*C*) corresponding to $t$ = 0.8 mm is $C = 1.1t = 1.1(0.8) = 0.88 \approx 0.9$ mm.

It was also decided that the final cup would have a depth of 20 mm and inner diameter of 50 mm, as shown in Fig. 3. Now, the blank diameter $D_b$ can be calculated using Eq. (8) [3, 6]:

$$D_b = \sqrt{d^2 + 4d(H - 0.43r)} \qquad (8)$$

where, $d$ = cup mean diameter (mm), $H$ = mean high of the cup's shell and $r$ = radius at neutral bend line. Using Eq. (8) and the cup dimensions of Fig. 3, $D_p$ is calculated to be $D_p$ = 80 mm. With $D_p$ = 80 mm, it can be shown that the three drawing feasibility measures are satisfied and the cup can be produced in a single stroke.

### *3.2 Determination of Drawing Force and Blank Holding Force*

The cup is to be produced from Yellow Brass C 26800 (65% Cu, 35%Zn) with $UTS$ = 332 MPa, $S_y$ = 98 MPa.

Using Eq. (5) with $D_p$ = 50 mm, one can calculate the drawing force to produce the cup as $F$ = 36.4 kN. Similarly, from Eq. (6), $F_h$ = 14 kN. So the total drawing force ($F_d$) to be applied by the DDM equals the summation of $F$ and $F_h$, that is $F_d$ = 50.4 kN. For design purposes of DDM elements, the $F_d$ shall be multiplied by a load factor equals to 1.6.

## 4. Design of the DDM Elements

This section presents the design of selected main elements of DDM. Fig. 4 shows a photo of the DDM and Fig. 6 shows a section of the DDM, its elements and the associated legend.

### *4.1 Design of the Die and the Punch*

Once the cup specifications have been determined, one can determine the specifications of the die and the punch being used to produce that cup. In particular, the punch must have an outer diameter equal to the inner diameter of the cup, i.e., of 50 mm. It also has to be high enough to produce the required depth (20 mm) of the cup. Hence, the punch was designed to have an outer diameter of 50 mm, punch radius ($R_p$) of 3.2 mm and a height of 80 mm. Die and punch are the mating parts in this process; therefore, the internal diameter of the die will be the same as punch outer diameter plus the compensation of the clearance between them. Fig. 5 illustrates the dimensions of the die.

### *4.2 Design/Safety Analysis of the Upper Support Plate*

The upper support plate, as its name indicates, is used to support the DDM by holding the hydraulic cylinder of the machine. Therefore, the design of this plate must be based on the maximum force provided by the hydraulic unit which equals 1.6 $F_d$ = 80 kN. Fig. 7 shows the dimensions of this plate, while Fig. 8 is the FBD (free body diagram) of the plate. As shown in Fig. 9, the loaded part of this plate can be approximated as a fixed support from both ends with a center load applied by the hydraulic unit. The reactions at A and C are same and equal to 40 kN, and the moments at A, B and C equal $M_A$ = 2,090 Nm, $M_B$ = 2,200 Nm, and $M_C$ = 2,090 Nm, respectively [4]. Section B (the mid span) is the critical section. Under this loading, the maximum normal stress in this section equals to 27.7 MPa. The plate is made of Hot Rolled steel with $S_y$ = 170 MPa. Hence, the factor of safety guarding against yielding of the upper plate equals 6.

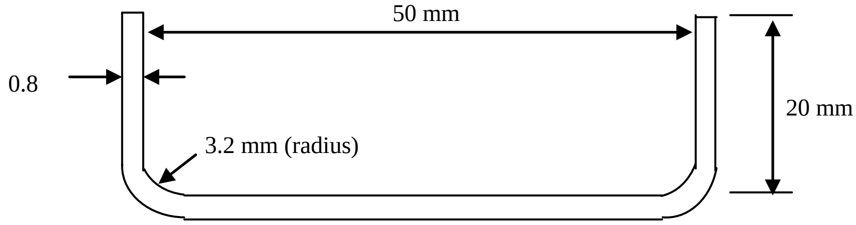



**Fig. 3 The final cup.**

**Fig. 4 Photograph of the DDM.**

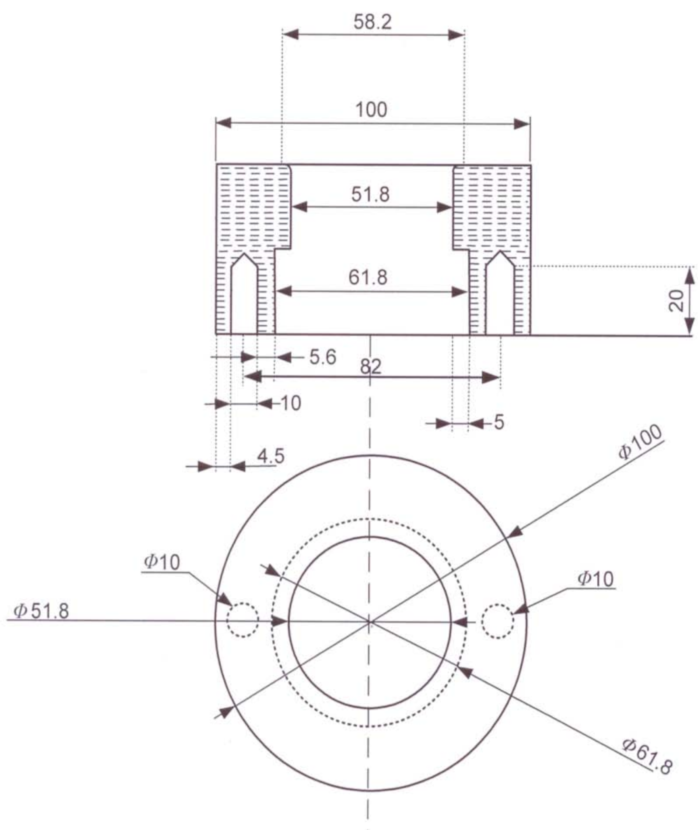
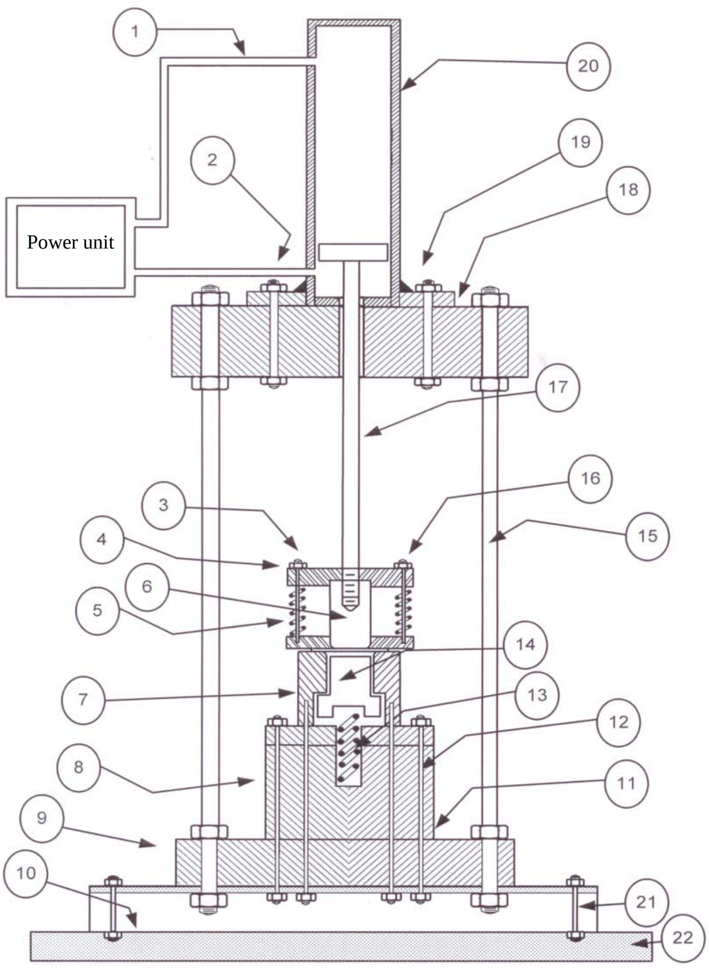



**Fig. 5 Die dimensions.**




(1) Hydraulic cylinder inlet
(2) Hydraulic cylinder outlet
(3) Blank holder upper plate
(4) Blank holding springs
(5) Blank holder lower plate
(6) The punch
(7) The die
(8) The die basement
(9) Machine basement
(10) Machine bench
(11) Lower support plate
(12) Lower support plate fixing screws
(13) Ejector spring
(14) Ejector
(15) Main supporting rods
(16) Blank holder fixing screws (M10)
(17) Arm of hydraulic cylinder
(18) Upper support plate
(19) Hydraulic cylinder fixing screws
(20) Hydraulic cylinder (Piston)
(21) Machine basement fixing screws
(22) Machine table

**Fig. 6 Section of the DDM: its elements and the associated legend.**

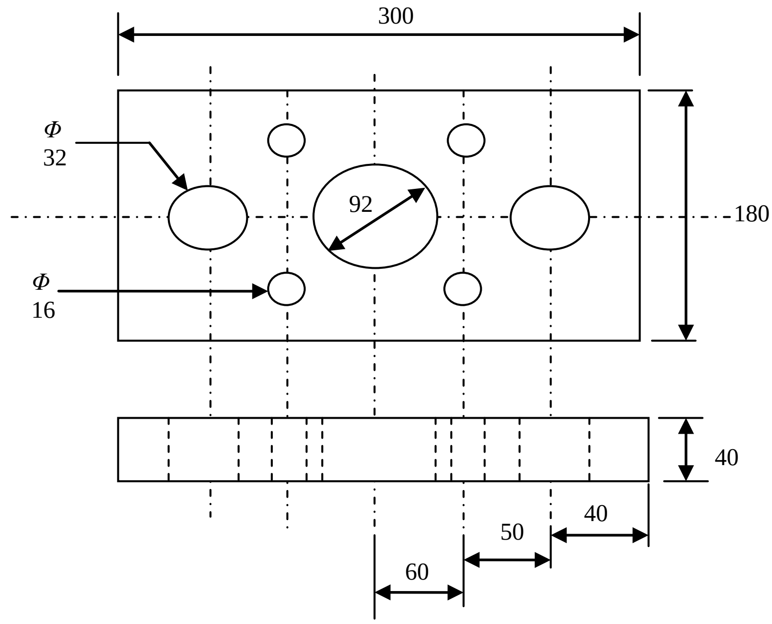



**Fig. 7 Dimensions of upper support plate (mm).**

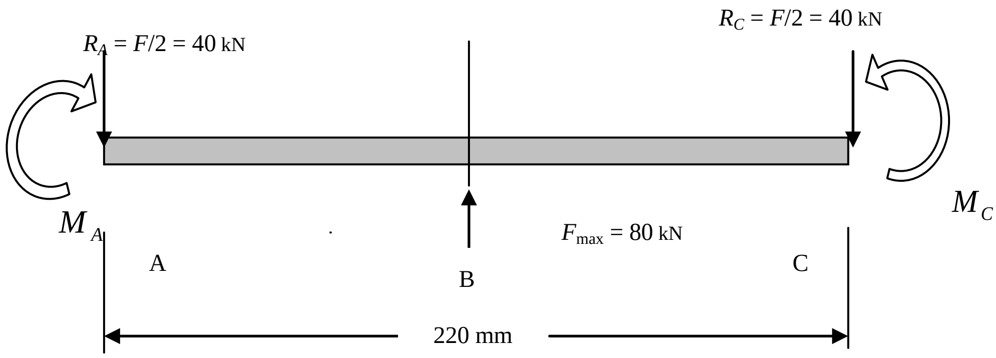



**Fig. 8 FBD of the upper support plate.**

*4.3 Design/Safety Analysis of the Main Supporting Rods*

The DDM is supported by two main rods, which are connected between the upper support plate and the lower support plate. The rods will carry equal loads, so what is applied to one will be the same as the other. Fig. 9 shows the FBD of one main rod. It can be shown that the combined normal stress in the rod due to axial and bending loads is around 160 MPa, and as the rod is made of stainless steel with $S_y$ = 240 MPa, then the factor of safety guarding against yielding of the rod will equal around 1.5.

*4.4 Design of the Blank Holder Unit*

This unit has three main parts, which are the upper and lower blank holding plates and the blank holding springs. The required blank holding force is transmitted from the hydraulic arm through the blank holding springs as a varying load to the blank holder lower plate which holds the blank. In order to exert the necessary holding force $F_h$, seven springs were used; each has stiffness ($K$) of 32 N/mm. The dimensions of one blank holding spring and the blank holding lower plate are shown in Fig. 10.

*4.5 The Ejector*

Once the punch completes its stroke, the blank holding unit is then moved upward and the final cup is ejected upward by the ejector which is connected to a spring with a stiffness ($k$ = 15 N/mm) to provide the required force needed for ejecting the cup. The dimensions of the ejector are shown in Fig. 11.

*4.6 Design of the Hydraulic System*

An important part of the DDM is the hydraulic unit, which provides the machine with the power needed to complete the drawing cycle. Three issues have to be considered in designing the hydraulic unite; these are the power required, the factor of safety of the hydraulic cylinder fixing screws, and that of the hydraulic cylinder weld between the cylinder and its flange. One horse power hydraulic pump is used in the DDM, and this power is enough to drive the punch at a speed of 10 mm/s. The internal diameter of the hydraulic cylinder is 80 mm, and the diameter of its flange is 180 mm.

## 5. Manufacturing and Assembly Operations

This section presents the manufacturing operations that were needed to produce DDM main parts (namely, the punch and the die). Most of these operations were metal machining and some welding.

*5.1 Die Manufacturing Operations*

The recommended material for deep drawing dies is mostly oil-hardened steel, which we used for producing the DDM die. A solid circular stock piece of oil-hardened steel was selected with a length 60 mm and a diameter of 110 mm. External and internal turning, fillet-making, drilling, threading and surface finish processes were used to produce the die.

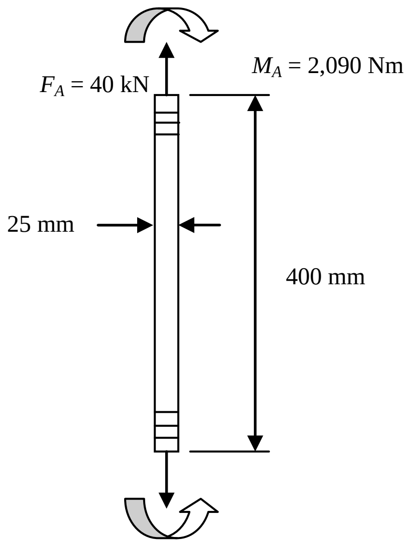



**Fig. 9 FBD of main rod.**

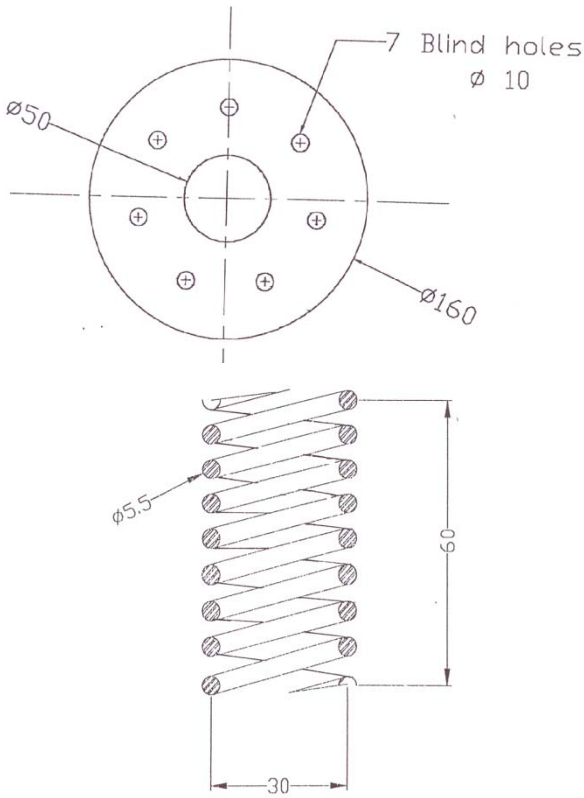



**Fig. 10 Dimensions of a blank holding spring and the blank holding lower plate (mm).**

*5.2 Punch Manufacturing Operations*

Likewise, the punch was made from the same material of the die—oil-hardened steel, which started with a solid stock piece with a length of 90 mm and a diameter of 60 mm. External turning, drilling, ventilation-holes and fillet-making processes were used to produce the punch.

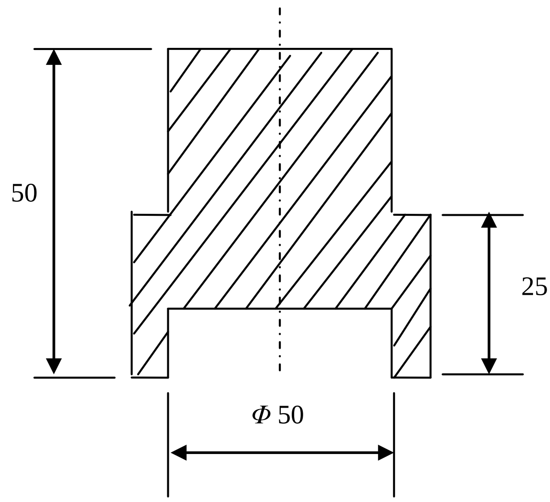



**Fig. 11 Dimensions of the ejector (mm).**

*5.3 Die and Punch Heat Treatment*

The mechanical properties of the punch and the die (especially the hardness) must be improved such that these two mating parts can handle the total drawing force without any type of distortion or deformation. To achieve this, preheating, quenching and tempering processes were used to heat-treat the die and punch. The hardness of the punch and the die before heat treatment was 300 VHN, after heat treatment, the hardness became 900 VHN. The hardness was measured using Vickers hardness tester available in the materials science laboratory at An-Najah National University. Once the DDM components have been manufactured and prepared, these elements were assembled with each other until the whole machine was totally constructed and operated.

## 6. DDM Operation and Experimentation

After the DDM had been designed, manufactured, and assembled, the machine was operated and tested to ensure appropriate operation and working. Then, two experiments were performed on the DDM: one is to investigate the relation between the drawing force

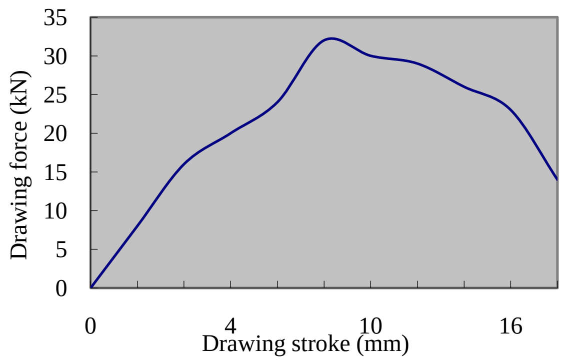



**Fig. 12 Sample result: drawing force vs. drawing stroke.**

(punch force) and the punch stroke, while the other experiment is to investigate and study the effect of strain factor on the LDR. A standard experiment handout was prepared for each of the two experiments to be used by students in the manufacturing processes lab. Fig. 12 demonstrates sample result on the relation between drawing force ($F = F_d - F_h$, $F_h$ is calculated by knowing springs deflection) and drawing stroke for brass cups, which agrees with the general trend shown in Fig. 12. The data are measured using pressure and dial gages. The results depicted in Fig.12 coincide with the results obtained in Ref. [7].

## 7. Conclusions

This paper presented the work done and experience gained in designing, constructing and operating a hydraulic deep drawing machine which is currently mounted in the manufacturing processes lab at An-Najah National University and used by students to perform experiments on deep drawing. We found the experience gained very useful in terms of obtaining a properly working DDM, as well as enhancing the students' abilities to understand the concept of deep drawing in particular and the concepts of design and construction of machines in general. The direct cost of the DDM was about $2,000, which is very cheap compared with a similar machine purchased from abroad.

## Acknowledgments

The authors would like to thank two anonymous reviewers for their valuable comments which greatly enhanced the quality of this work.

## References

[1] Groover, M. P. 1996. *Fundamentals of Modern Manufacturing: Materials, Processes and Systems.* New Jersey: Printice-Hall Publishing.

[2] Schey, J. 1987. *Introduction to Manufacturing Processes.* New York: McGraw-Hill Publishing.

[3] Hosford, W. F., and Caddell, R. M. 1983. *Metal Forming, Mechanics and Metallurgy.* New Jersey: Prentice Hall.

[4] Shigley, J. 2008. *Mechanical Engineering Design.* New York: McGraw-Hill Publishing.

[5] Karali, M. 2011. "Examination of the Strength and Ductility of AA-1050 Material Shaped with Multi-stage Deep Drawing Method." *Archives of Metallurgy and Materials* 56 (2): 223-30.

[6] Edwards, G. H. 1984. *Fundamentals of Tool Design.* 2rd edition. Michigan: SME.

[7] Demirci, H. Y., Yaşar, M., Demiray, K., and Karali, M. 2008. "The Theoretical and Experimental Investigation of Blank Holder Forces Plate Effect in Deep Drawing Process of AL 1050 Material." *Materials & Design* 29 (2): 526-32.

[8] Kalpakjian, S., and Schmid, S. 2007. *Manufacturing Processes for Engineering Materials.* 5th edition, New Jersey: Prentice-Hall Publishing.

[9] Gea, H. C., and Ramamurthy, R. 1998. "Blank Design Optimization on Deep Drawing of Square Shells." *IIE Transactions* 30: 913-21.

[10] Reddy, R. V., Reddy, T. A., and Reddy, G. C. M. 2012. "Optimization of Blank Holder Force to Control Wrinkling and Fracture of Cylindrical Cups in Deep Drawing." *International Journal of Engineering Trends and Technology* 3 (5): 669-76.

[11] Wang, X, and Cao, J. 2000. "On the Prediction of Side Wall Wrinkling in Sheet Metal Forming Processes." *International Journal of Mechanical Sciences* 42: 2369-94.