論文 한국정밀공학회지 제4권 제1호 1987.
Journal of the Korean Society of Precision Engineering Vol. 4, No. 1Mar., 1987

A Study on the Computer-aided Control of the Blankholder Force in the Deep Drawing Process

Chang-Seop Song*, Daeyong Lee**

딥드로잉에서의 소재누르기 힘의 컴퓨터제어에 관한 연구

송 창섭*, 이 대용**

요 지

딥 드로오잉 시의 소재누르기판의 힘을 펀치의 변위 혹은 힘의 임의의 함수로서 제어시킬 수 있는 서브프레스장치 및 유압장치를 제작하고 제어용 프로그램을 작성하여 시험하였다. 제작한 장치를 인스트론 시험기에 설치하고 제어용 프로그램을 IBM퍼스널 컴퓨터를 사용하여 실행시킨 결과, 기계 제어 부분은 어셈블러언어로, 계산 부분은 고급언어로 프로그램을 작성하여 링크시킨 후에 컴파일링하여 사용하는 것이 제어의 응답성 및 정확도를 향상시킬 수 있음이 판명되었다. 또한, 소재누르기판의 힘의 제어에 필요한 이론 및 예비 결과들도 제시하였다.

I. INTRODUCTION

Deep drawing is one of the most common sheet material forming processes. In its simplest form, a flat sheet is held between the die and blankholder along its circumference and the punch pushes the middle portion of the sheet to form a drawn cup. As the sheet bends over the die radius thereby forming a cup wall, a biaxial state of tensile stress develops in the cup wall. If the tensile stress exceeds the ultimate stress of the material, the wall section may undergo necking and failure. The magnitude of tensile stress in the cup wall is, however, dependent on the clamping force between the die and blankholder, as well as punch and die geometry, material properties, initial blank size, and sheet thickness, etc.(1) Therefore, the blankholder force may play an important role in determining the drawability of sheet material forming processes.

---

* 한양대학교 공과대학 정밀기계공학과 조교수

** Professor of Mechanical Engineering, Rensselaer Polytechnic Institute, Troy, Ny 12181, U.S.A.

As the sheet material is drawn into the cup form by the punch, the material in the flange section undergoes a tensile stress in the radial direction and a compressive stress in the circumferential direction, as shown in Fig. 1. This circumferential compressive stress can cause wrinkles as the sheet buckles locally.

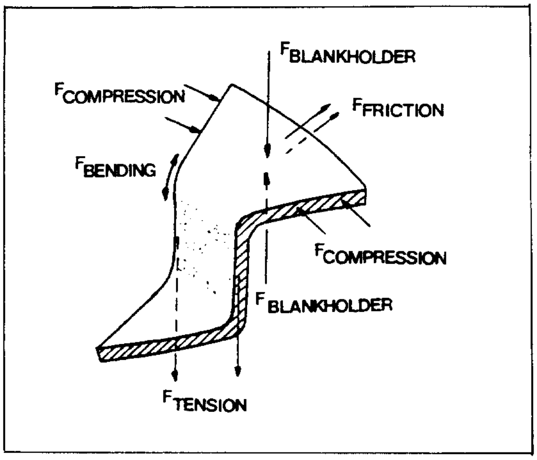


Fig. 1 A schematic illustration of forces acting on the flange section in deep drawing. Wrinkles and cracks are due to $F_{COMPRESSION}$ and $F_{TENSION}$, respectively.

Wrinkles may be avoided by the application of the blankholder pressure, but the optimum amount of pressure necessary to avoid wrinkling is not well established. Furthermore, the blankholder pressure may be varied either as a function of punch displacement or punch load. Whether such a variable blankholder pressure will aid the deep drawing process is not fully understood at the present time. Further development work is needed to establish the relationships between punch load, deep drawability, geometry, functional boundary conditions, and blankholder pressure for different types of drawing processes.

II. FURTHER DESCRIPTION OF THE DRAWING PROCESS

Although the cup drawing may appear simple, a thorough analysis of the forming process is rather difficult. Aside from recent application of finite element analysis method, a number of authors have made attempts to obtain analytical solutions for simple axisymmetric configurations.(2-6)

Perhaps a simplest analysis method was outlined by Siebel.(2) From the equilibrium condition in the radial direction, the required drawing load and its variations along the punch stroke was determined analytically. The following equation for calculating the drawing load, F_d, has been proposed.

$$F_d=\pi d_m S_o \left[\exp(\mu\pi)/2{*}1.1\,\sigma_{f,m} \ln(d/d_m)+\mu(d-d_m) \cdot P_{bh}/S_o+\sigma_{f,m}(S_o/2r_d)\right] \cdots\cdots (1)$$

where d_m is the mean wall diameter, d is the instantaneous outside radius of the flange, S_o is the blank thickness, r_d is the die radius, $\sigma_{f,m}$ is the mean value of flow stress of the blank material, μ is the coefficient of friction between flange and die or blankholder, and P_{bh} is the blankholder pressure. In Eq. (1), the first term represents the ideal deformation load including the load increase due to friction at the die radius, the second term is the component produced by friction between the flange and die or blankholder, and the last term is the load necessary for bending the sheet around the die radius.

A typical load-stroke diagram for deep drawing is shown in Fig. 2, indicating that the flow stress increases continuously with punch displacement as the flange diameter becomes smaller.(1) Siebel and Beisswanger have suggested that the maximun drawing load is nearly independent of the workpiece material and drawing ratio and occurs when d = $0.77d_o$, where d_o is the initial blank diameter.(2)

If the maximum drawing load reaches beyond the failure load, then fracture may occur near the bottom punch radius. Therefore, the blankholder force control may be desirable to prevent failure because drawing load is related to the blankholder pressure, as indicated in Eq. (1).

As long as the blank is clamped rigidly between the blankholder and die, buckling cannot occur. During cup formation the sheet thickness in the flange does not remain constant but increases toward the

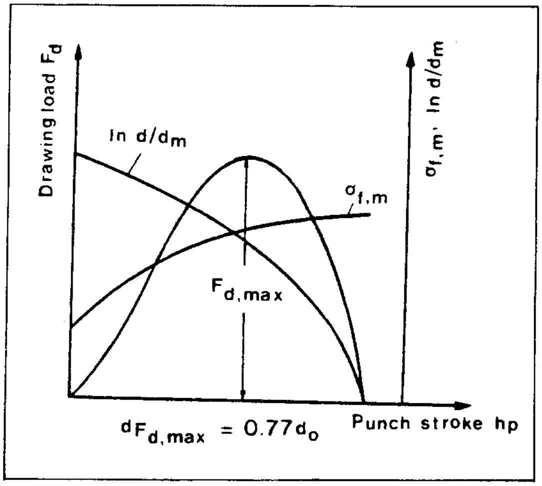


Fig. 2 Variation of drawing load, F_d, flow stress, $_{f,m}$, flange diameter reduction ratio, $\ln(d/d_m)$, to cup wall mean deameter, d_m, with increasing punch stroke. The figure is taken from ref. 1.

outside edge while the center portion near the die radius becomes thinner than the initial thickness, S_o, in the early stages of the draw. Since the distance between blankholder and die is determined by the largest flange thickness, there will be a gap between the blankholder and sheet near the die radius. This gap may create an opportunity for the initiation of wrinkles. Thin sheets (d_o/S_o > 25-40) are especially sensitive to wrinkle formation because their moment of inertia in buckling is relatively small. The pressure necessary to avoid wrinkling depends on the material properties, the relative sheet thickness, and the drawing ratio. Earlier work by Siebel and Beisswänger showed that the required blankholder pressure could be estimated from the following empirical equation (2).

$$P_{bh}=10^3c\left[(\beta-1)^3+0.005\,(d_o/S_o)\right]S_u \cdots\cdots\cdots (2)$$

where the factor c ranges from 2 to 3, is the drawing ratio, which is defined as the ratio of the initial blank diameter d_o to the inside diameter of the finished cup d_1, and S_u is the ultimate tensile strength of the material.

The flange wrinkling behaviour of sheet materials in deep drawing operations was futher analyzed by Senior(7) and Alexander(8). Their expression for the blankholder force is given below:

$$P_{bh}=E_o t^3\gamma(b^4n^4-7.46a^4)\ 30.54\,a^4b^3 \cdots\cdots\cdots (3)$$

where the buckling modulus E_o is equal to $4EP/(E^{1/2}+P^{1/2})^2$, where E is the elastic modulus and P the tangent modulus, t the sheet thickness, γ wrinkle amplitude, b the flange width, n the number of wrinkles, and a the mean radius of flange. Equation (3) shows that the blankholder force increases with the flange width in a complicated fashion. The main point is that the functional relationship between the blankholder force and the depth of draw under the ideal condition is indeed complex.

Qualitatively, it is conceivable that a proper control of the blankholder force may reduce fracture and wrinkles in a simple drawing operations while reducing the punch load at the same time. In fact, possible ranges of the variation of minimum and maximum allowable blankholder force along the drawing depth have been shown by Doege and Sommer(9), as shown in Fig. 3.

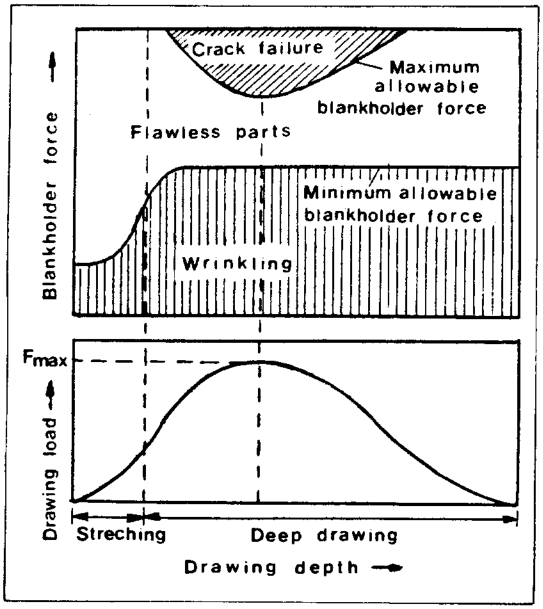


Fig. 3 Maximum and minimum allowable blankholder force with increasing drawing depth. The figure is taken from ref. 9.

III. DRAWING APPARATUS AND FORCE CONTROL

3.1 Drawing Subpress Assembly

The drawing subpress assembly consists of three plates as shown in Fig. 4. A punch which is fixed at the center of the punch plate driven by the cross head of an Instron testing machine moves along the guide rod fixed at the die plate. Since the blankholder plate which can be moved along the same guide rod is connected to the piston rod of a hydraulic cylinder by four bars, the blankholder force can be controlled by the hydraulic pressure applied in the hydraulic cylinder.

At both die plate and blankholder plate, heating elements are installed to perform experiments for the drawability in the presence of temperature gradient(10).

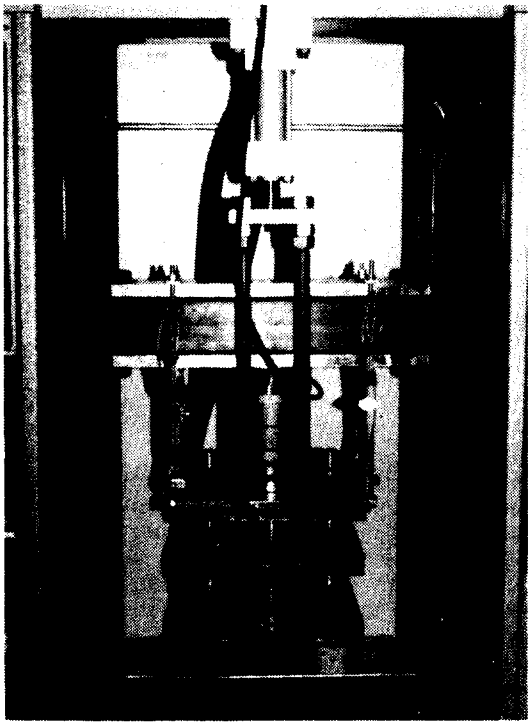


Fig. 4 The photograph of the subpress assembly installed in an Instron testing machine. The punch plate is driven by the cross head of Instron testing machine, and the blankholder plate by a hydraulic cylinder

3.2 Blankholder Force Control

A hydraulic pressure control system is used to control the blankholder force. A schematic diagram of the hydraulic control system is shown in Fig. 5. The pressure in the hydraulic cylinder connected to the blankholder plate can be controlled by a pilot type pressure relief valve. The pilot vent line of the pressure relief valve is connected to an electrically modulated relief valve which has a function of converting electrical signal into hydraulic pressure.(11) The resulting output pressure is not directly proportional to the input current due to the nonlinearity between input current and output force of the electromagnet in the electrically modulated relief valve. The input current is generated from the electronic power supply which converts the input voltage into the output current in proportion. Therefore, the nonlinearity of the electrically modulated relief valve must be compensated in order to have a proportional relationship between input voltage and blankholder force generated by the hydraulic cylinder.

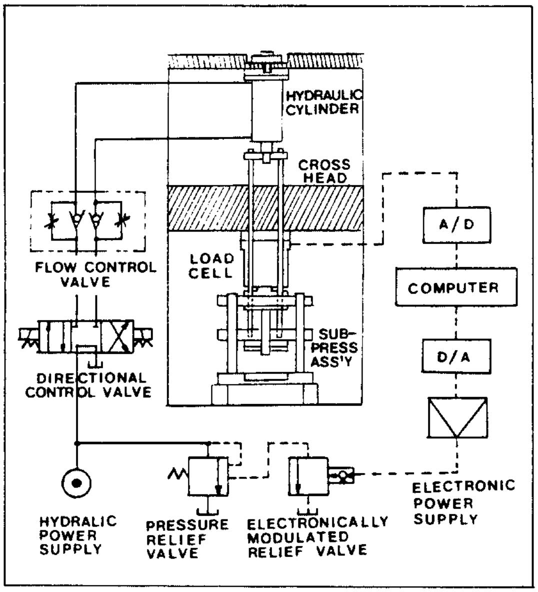


Fig. 5 Schematic diagram of the hydraulic control system for blankholder force control. Blankholder speed and force are controlled by a flow control valve and a pressure relief valve combined with a electrically modulated relief valve, respectively.

This compensation can be provided by a microcomputer program.

Two types of blankholder force control programs have been developed. One program can generate the blankholder force signal as a function of the drawing depth, and the other program as a function of the drawing load.

3.2-1. Control Algorithm in terms of Drawing Depth

The drawing depth can be estimated by knowing the elapsed time after the punch makes a contact with the blank since the punch speed is constant in the Instron machine. If a load cell is attached to the punch, the change of signal from the load cell can be used as a means of detecting punch and blank contact time. The elapsed time corresponding to drawing depth can be checked by the supplied TIMER function or by using the programmable interval timer chip equipped for the TIMER function directly.(12) The latter method is preferred than the former from the viewpoint of time resolution and accuracy.

The control program can make output signal as a user defined function of drawing depth. There are two kinds of control algorithm. One is the post-calculation methed by which the output signal is calculated after each drawing depth is inputed. The other is precalculation methhod by which all the necessary output signals are calculated and stored into memories and then outputed sequentially. The latter method needs more memory space, but it can make the response time shorter.

The flow diagram of the blankholder force control as a function of drawing depth is shown in Fig. 6, where an IBM PC is used with a commercial A/D and D/A converter board called Lab Master.(12)

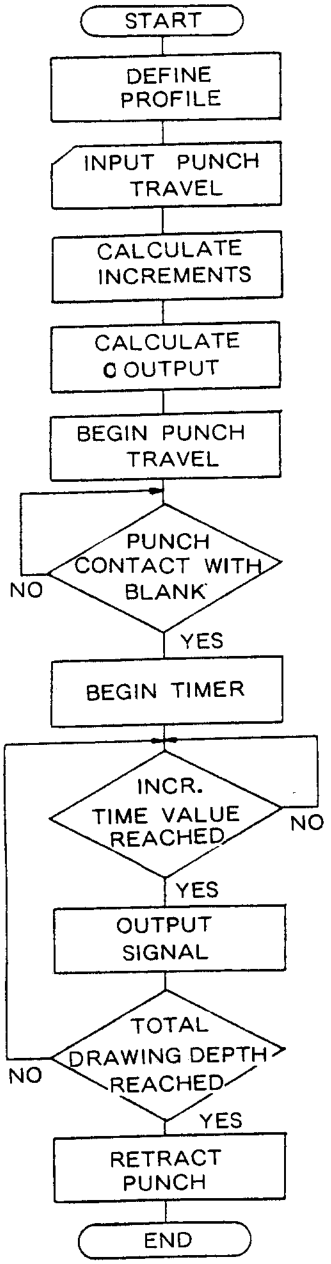
This algorithm uses a pre-calculation method for the output signal generation while compensating for the nonlinearity of the electrically modulated relief valve. The drawing depth is measured by a time checking program written by an assembly language for the programmable interval timer, Intel 8253, in an IBM PC.(14)

3.2-2. Control Algorithm in terms of Drawing Load

The drawing load as measured from the load cell is used for this control. In addition to the voltage signal from the load cell providing the drawing load, the first change of the signal as the punch touches the blank can be used as the starting point.

The control output signals are generated as a user defined function of drawing load and are modified to compensate for the nonlinearity of the electrically modulated relief valve. Again, these calculations can be made by two methods, as described before. In the precalculation method, it is necessary to search for the output signal because the output signal data are calculated and stored in the order of increasing drawing load sequentially. If an n-bit A/D converter is used as the input channel, then the number of different data which can be inputed from the A/D converter can not exceed 2^n, and the maximum number of output data calculated from the input data is equal to 2^n. The output data should have the 2 byte integer number form so that the D/A converter should handle the output readily. The maximum required memory size for sorting the calculated output data becomes 2^{n+1}.

The output data search in the case of the pre-calculation method is done as follows. Since the calculated output data are stored sequentially in a form of integer array, each data occupies 2 byte memory. If the address number of the first data location is known, the output data can be found at the memory location whose address number is the sum of address number of the first data and two times of input data received from the A/D converter. This and next memory data become the output data corresponding to the input data. Twice the value of input data can be obtained easily by shifting one bit left in an assembly language program. The main part of control algorithm for the blankholder force as a function of the drawing load is shown in Fig. 7.



Force control program start.

Define flange area and blankholder pressure profile as a function of drawing depth.

Input total drawing depth and punch feedrate.

Calculate time increment and total count number from the drawing depth interval and total drawing depth.

Calculate output signals at every drawing depth interval and store them at memories sequentially.

Output a blank clamp signal and then a punch feed signal toward the blank.

Is the signal from the load cell attached to the punch changed?

Reset the count number and make the internal timer to be operated.

Does the elapsed time of the timer reach to the time increment?

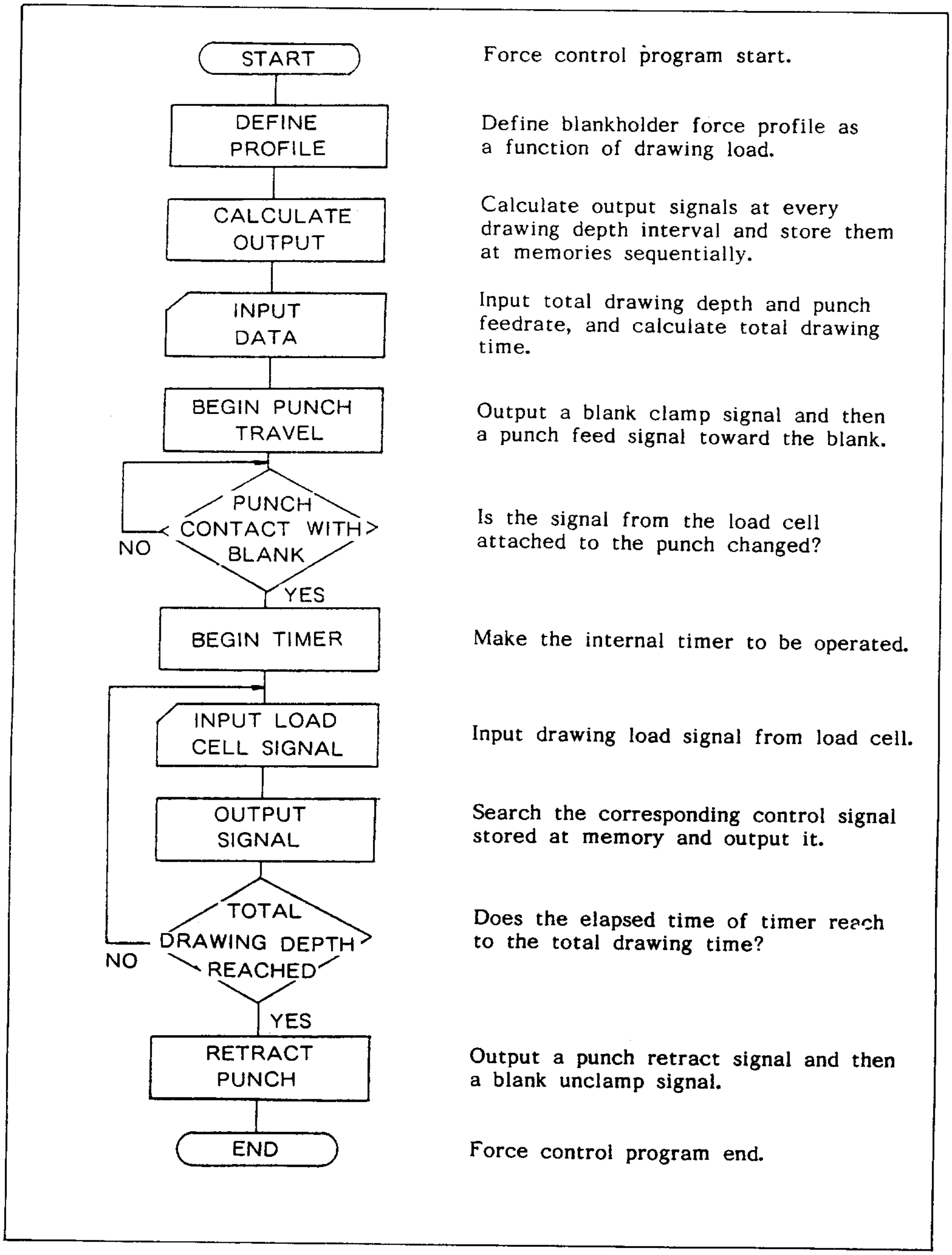
Output the pre-calculated control signal stored at specified memory and increase the memory location and the count number one more.

Does the present count number reach to the total count number?

Output a punch retract signal and then a blank unclamp signal.

Force control program end.

Fig. 6 Flow diagram for blankholder force control in terms of drawing depth. Blankholder force is controlled by a user defined blankholder pressure profile as a function of drawing depth.



Force control program start.

Define blankholder force profile as a function of drawing load.

Calculate output signals at every drawing depth interval and store them at memories sequentially.

Input total drawing depth and punch feedrate, and calculate total drawing time.

Output a blank clamp signal and then a punch feed signal toward the blank.

Is the signal from the load cell attached to the punch changed?

Make the internal timer to be operated.

Input drawing load signal from load cell.

Search the corresponding control signal stored at memory and output it.

Does the elapsed time of timer reach to the total drawing time?

Output a punch retract signal and then a blank unclamp signal.

Force control program end.

Fig. 7 Flow diagram for blankholder force control in terms of drawing load. Blankholder force is controlled by a user defined blankholder force profile as a function of drawing load.

IV. EXPERIMENTAL RESULTS

Four control programs in terms of variations in program language and their compiled versions were tested. It was shown that the control response could be increased by about 8 times by combining the machine control program written by an assembly language as compared to the compiled BASIC program with the same control algorithm. At the same time, the computation time for the output signal was reduced by about 1/6 to 1/8 of that obtained in the interpreted version of the program.

Applying these control procedures, several axisymmetric cups were formed from the 2.5mm thick polypropylene sheets containing 40% by weight calcium carbonate, the same polymer sheets used in previous work.(10) In order to examine the simplest cases of the blankholder force control, only the magnitude of the blankholder force was varied while keeping the load constant during each drawing process. Selected cups formed while applying different levels of blankholder forces are shown in Fig. 8.

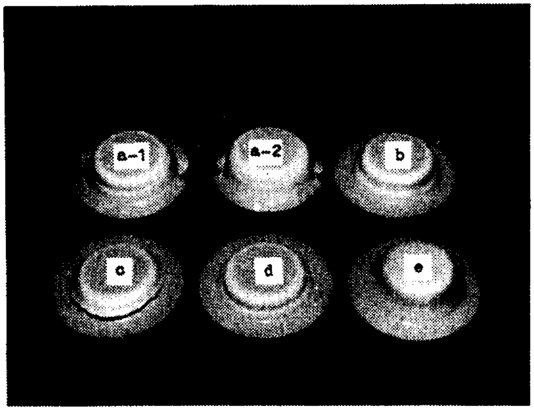


Fig. 8 A photograph of cups drawn with 2.5mm thick and 7mm diameter blanks at different blankholder force: (a) without blankholder force, (b) with 50 lbs. blankholder force, (c) with 300 lbs. blankholder force, (d) with constant blankholder position, (e) with lubricating film between blank and blankholder or die at 50 lbs. blankholder force.

The extreme case of not applying any blankholder force is shown in Fig. 8a, where the formed cup has several wrinkles. Some of the wrinkles formed during the drawing process sometimes recovered completely during the unloading of the punch. The drawn cup without cracks and wrinkles as shown in Fig. 8b could be obtained in the case of appropriate blankholder force (about 50 lbs) applied, but a crack occured as drawing was more progressed. When excessive blankholder force (about 300 lbs) was applied, wrinkles did not appear but a crack began to occur at the cup wall even though shallow drawing depth as shown in Fig. 8c. If the blankholder positon was controlled to be constant, the drawn cup without wrinkles as shown in Fig. 8d could be obtained but cracks might be occured in the case of large drawing ratio. Fig. 8e shows a deeper drawn cup when two lubricating films such as teflon sheet was inserted between blank and blankholder or die.

V. CONCLUSIONS

A computer-aided blankholder force control system was developed to examine effects of blankholder force in deep drawing processes. Some of the concluding remarks are summarized as follow.

(1) The blankholder force control in terms of drawing depth or drawing load is feasible for deep drawing process by a computer controlled mechanical/hydraulic system. In this way, an optimum force history may be obtained for improved deep drawability.

(2) The control speed and accuracy of the blankholder force control system can be improved by using a compiled program combined with an assembly program for machine control.

(3) Preliminary test results with polypropylene sheets have shown that an appropriate blankholder force application could increase the drawing depth without cracks or wrinkles.

VI. ACKNOWLEDGMENTS

On of the authors (C. S. Song) was

supported by the Ministry of Education in Korea and a portion of this material is based upon work supported by the National Science Foundation of U.S.A. under Grant No. DMC-8415309.

REFERENCES

1. K. Lange, "Handbook of Metal Forming", McGraw-Hill book Co., pp.20.1-20.21, 1985
2. E. Siebel and H. Beisswänger, "Deep Drawing"(in German), Munchen, Carl Hansen Verlag, 1955
3. S. Rajagopal, " A Deep Drawing Test for Determining the Punch Coefficient of Friction", ASME Journal of Engineering for Industry, Vol.103, pp.197-202, 1981
4. D.M. Woo, "Analysis of Deep-Drawing over a Tractrix Die", ASME Journal of Engineering Materials and Technology, Vol.98, pp.337-341, 1976
5. J.O. Kumpulainen, A.J.Ranta-Eskola and R.H.O. Rintamaa, "Effects of Temperature on Deep Drawing of Sheet Metals", ASME Journal of Engineering Materials and Technology, Vol.105, pp.119-127, 1983
6. D.M. Woo, "On the Complete Solution of the Deep-Drawing Problem", Int. J. Mech. Sci., Vol.10, pp.83-94, 1968
7. B.W. Senior, "Flange Wrinkling in Deep-Drawing Operations", J. Mech. Phys. Solids, Vol.4, pp.235-246, 1956
8. J.M. Alexander, "An Appraisal of the Theory of Deep Drawing", Met. Review, Vol.5, pp.349-411, 1960
9. E. Doege and N. Sommer, "Optimization of Blankholder Force During Deep Drawing of Rectangular Parts", Stahr u. Eisen 103, Nr.3, pp.139-141, 1983
10. T. Machida and D. Lee, "Deep Drawing of Polypropylene Sheets under Differential Heating Condition", To be published in Polymer Eng. and Sci., 1986
11. N.D. Vaughan, "A Review of Electrohydraulic Modulating Valves for Microprocessor Control", Proceeding on IMechE on Microprocessors in Fluid Power Engineering, C236/84, 1984
12. L.C. Eggebrecht, "Interfacing to the IBM Personal Computer", Howard W. Sams & Co., Indianapolis, IN, pp.117-124, 1983
13. Scientific Solutions Manual, "User's Guide for LabMaster", Scientific Solutions Inc., Solon, OH, 1985
14. IBM Manual, "Technical Reference for IBM Personal Computer", Rev. ed.(2.02), IBM Corp., Boca Raton, FL, pp.D.19-20, 1983