Process simulation for can manufacturing using deep drawing and ironing

A scientific look at how CAE techniques might be useful for tool design and manufacturing

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Deep drawing and ironing are the major processes used today in manufacturing of most beverage cans from aluminum. The same technology is used in manufacturing of steel cans for the food industry. The practical aspects of this technology are well known and increased through extensive experimentation and production know-how.

The fundamental aspects of the processes, however, are relatively less known, especially regarding the temperature developed during deformation and the effect of deformation speed on temperatures and lubrication. Therefore, it is expected that process simulations using finite element modeling (FEM) techniques would provide additional details that could be used to improve the process conditions.

This article describes how process modeling was applied to deep drawing and ironing operations. The predictions agree well with the experiment results. Parametric studies (computer simulations of the metal flow using different die angles, friction coefficients, and thickness reductions), although applied only to a single die operation, illustrate the interactions between process variables.

Introduction

Since the early 1970s, deep drawing and ironing have been the major processes for manufacturing beverage cans and deep round cups. With the advance of technology, deeper cups with thinner walls can be produced. Presses with relatively longer strokes—600 to 750 millimeters—and higher speeds—400 strokes per minute (SPM)—are used for the operation. Aluminum and its alloys are used as the primary can material.

Cans are produced by simultaneous deep drawing-redrawing and a number of ironing operations (see Figure 1)\(^1\). The punch is guided by the hydrostatic bushing, labeled A in Figure 1, and the mixing of the ironing lubricant and the hydrostatic bushing oil is prevented by the front seal, labeled B in Figure 1. The drawn cup is automatically fed between the redraw die D and the redraw sleeve C.

After the part is redrawn through D, it is ironed through the ironing dies E. In the last step, the bottom of the cup is domed by I. When the punch starts its return motion, the can is removed from the punch by the mechanical stripper G assisted by the air stripper F in Figure 1.

Originally, the beverage can consisted of three steel pieces: a rolled and seamed cylinder and two end pieces. The first aluminum can, which consisted of two pieces, was introduced in 1958. It was produced by impact-backward extrusion from a circular slug. However, this technique was found to be slow, and tooling problems plagued the process.

In 1963, the first modern deep drawn-ironed two-piece can was produced by Reynolds Metal. Until today, most of the technological progress was made to reduce the metal used in the can because the aluminum represents half the cost of the can. Reducing the can’s mass by 1 percent will save $20 million a year in aluminum, considering the 300 million cans a day production in the U.S.

Shawki studied the effects of die geometry and friction conditions on the ironing of axisymmetric cartridge brass cups by performing ironing experiments\(^2\). He reported that increasing the die throat length, \(l\), as shown in Figure 2a, increases the punch load. This is because of the increased frictional force which results from the increased interface area between the sheet and the tools. On the other hand, small die throat lengths reduce the dimensional and surface accuracy of the sheet.
Research on This Topic

Lahoti and others examined the effects of die profile on the ironing of shells/cups. They created a theoretical velocity field model and compared the predictions with the experimental measurements by Busch; in which the predictions agreed well with the measurements. Then, the analysis was used to investigate the effects of various die profiles on the process. Murty and others studied the feasibility of using a flexible mandrel in the ironing of thick walled nonferrous cups.

Both experimental and theoretical investigations have been carried out to determine the effects of the various process parameters such as the die angle, the mandrel hardness, the reduction ratio, the cup wall thickness, etc. Schmid and Reissenner developed an analytical model based on Hill's instability criterion to predict the ironing limit. Their experimental measurements showed that the experimental ironing limits correspond to the predictions of the analytical model. They also reported that a high friction coefficient at the punch-sheet surface reduces the axial force carried by the cup walls. Therefore, a higher ironing ratio would be feasible. However, the admissible value of this friction coefficient is limited by surface scratching which is likely to occur when the ironed cup is removed from the punch.

Jianjun studied the prediction of the ironing force by using the slab analysis. His comparisons of the predictions with the experimental measurements proved the analysis to be reasonably accurate.

Kasuga and others studied the simultaneous process where deep drawing and ironing are done simultaneously (see Figure 2b). Wolf and others also studied the simultaneous process. They reported that the maximum wall thickness reduction by the simultaneous process is highly affected by the workpiece material, the die angle, the deep drawing ratio, and the lubrication conditions. The maximum thickness reduction in the simultaneous process is always smaller than that in the case of simple ironing because of the additional stretching of the sheet by the frictional resistance force at the flange region. However, as the deep drawing ratio is reduced, the maximum thickness reduction increases and becomes closer to that in the case of simple ironing process.

Wolf and others also reported that the accuracy, as well as the maximum wall thickness reduction, is dependent on the die throat length, "l," in Figure 2a. Although the punch load is reduced with decreasing die throat length, it cannot be reduced significantly because that would increase the die wear and reduce the workpiece's dimensional and surface accuracy. Finally, wall thickness reductions of 10 to 15 percent can be achieved with the simultaneous process.

Aoki and Miyauchi studied the bith-sided ironing process where ironing is done on both surfaces of the cup wall. In their further studies, the geometry of the inner die was modified to obtain optimum results.
Tirosh and others examined the hydrostatic ironing process where the cup is subject to a hydrostatic pressure before it enters the ironing die. Subramanian and others studied the hot and cold tandem ironing operations which employ a tapered punch. Lambert and others examined the stress and force analysis of multiple die ironing including the effects of the process variables on the die pressures, forces and the limits of the process.

Hamann studied the ironing of axisymmetric cups with thick walls which are deep drawn without a blankholder. Kerspe studied the ironing of stainless steel cups, including the tribological effects of the process variables.

**Process Simulations**

Drawing, redrawing, and ironing of aluminum sheet were simulated with DEFORM 2D software, a rigid-plastic (ignoring elastic behavior of the material) finite element program which was originally developed for billet forming applications. However, the applicability of DEFORM 2D to sheet metal forming simulations was tested at the Engineering Research Center for Net Shape Manufacturing (ERC/NCM), and it was found to be reliable despite long central processing unit (CPU) times.

The long CPU times were needed for two reasons:

1. The high number of elements needed to model the workpiece, since the finite element program generates brick elements.
2. In billet forming, the sliding of the workpiece is fairly small; or, in cases where sliding is large in billet forming
(extrusion), the majority of the workpiece is in contact with the tooling. However, in sheet forming—especially in drawing/redrawing—there is large sliding between the sheet and the tools, and the contact between the sheet and the tools changes continuously due to the drawing-in or local thickening of sheet which causes the contact between the thinner parts of the sheet and the tools to vanish.

Deep drawing and redrawing simulations. To simulate the ironing process as closely to reality as possible, deep drawing of aluminum alloy AA 3104-H19 using a blank of 0.292-mm initial thickness was simulated initially. The process parameters were as follows:

- Material: A 3104-H19
- Blank diameter ($d_b$): 139.7 mm
- Initial thickness ($t_0$): 0.292 mm
- Punch diameter ($D_p$): 90.551 mm
- Punch profile radius ($r_p$): 3.175 mm
- Die diameter ($D_d$): 91.2114 mm
- Punch-die clearance ($|D_d-D_p|/2$): 0.3302 mm
- Die profile radius ($r_d$): 6.35 mm
- Friction coefficient ($\mu$): 0.08 (on all surfaces)
- Blankholder force: 44.6 kN
- Punch speed: 5.080 mm/sec (constant)

Figure 3 illustrates the geometry of the tooling and the sheet at an intermediate step of the deep drawing simulation. The material properties are given as $K=360$ MPa, $n=0.06547$ for $\sigma=K\epsilon^n$. Since the flow stress of the material is not defined as a function of deformation rate, the punch speed does not have an effect on the flow stress.

The appropriate value of the blankholder force (44.6 kN) was determined by trial-and-error when fracture at the corner of the cup was detected for higher blankholder forces and the flange lifted the blankholder for lower blankholder forces. From the simulation, the height of the cup was found to be 32.21 mm, while height measurements from the sample cup varied between 30.66 mm to 32.64 mm (effect of earing).
The comparison of the wall thickness distribution between the predicted and the measured values is illustrated in Figure 4. As the figure shows, the predictions are in good agreement with the measurements.

After the deep drawing simulation, the redrawing process was simulated by keeping the strain history of the cup with the following process parameters:

- Material: A 3104-H19
- Cup initial internal diameter ($d_0$): 90.551 mm
- Punch diameter ($d_p$): 65.8876 mm
- Punch profile radius ($r_{p1}$): 5.08 mm
- Die diameter ($D_d$): 66.548 mm
- Punch-die clearance ($d_d - d_p$): 0.3302 mm
- Die profile radius ($r_d$): 6.35 mm
- Blankholder profile radius ($r_b$): 3.175 mm
- Friction coefficient ($\mu$): 0.08 (on all surfaces)
- Blankholder force: 2.22 kN
- Punch speed: 5.08 mm/sec (constant)

Figure 5 illustrates the geometry of the tooling and the sheet at an intermediate step of the redrawing simulation, which lasted 40 CPU hours on an IBM RISC-6000 workstation with 718 elements in the sheet. The appropriate value of the blankholder force (2.22 kN) was determined by trial-and-error when fracture at the corner of the cup was detected for higher blankholder forces and the flange lifted the blankholder for lower blankholder forces.

From the simulation, the height of the cup was found to be 58.384 mm, while the measurements from the sample cup varied between 54.61 mm to 58.674 (effect of earing).

The comparison of the wall thickness distribution between the predicted and the measured values is illustrated in Figure 6. As the figure shows, the predictions are in good agreement with the measurements even though the measurements were limited to a certain depth.

### Ironing Simulations (A Parametric Study)

After the redrawing simulation, the tooling was changed to the ironing tooling while the deformation history of the sheet was maintained. To obtain accurate simulation results, the number of elements through the thickness direction was increased to four. However, this resulted in a very large number of elements (3,300 elements) which took about 75 CPU hours to complete a 20 percent thickness reduction simulation on an IBM RISC-6000 workstation. To solve this problem, the cup was cut at a height of 20.32 mm so that the number of elements used could be reduced.

With the new sheet geometry, we were able to generate a mesh of four elements through the thickness direction. This resulted in a total of 1,000 elements and cut the CPU time of one simulation down to 6 CPU hours. Therefore, the ironing simulations were run for a cup geometry of 20.32 mm height.

Four process parameters were varied during the ironing simulations:

- Thickness reduction: 20 percent, 27.5 percent, 35 percent, and 42.5 percent
- Die angle: 7.5°, 10°, and 12.5°
- $\mu_1$: 0.05, 0.1, 0.15 (on the punch-sheet surface)
- $\mu_2$: 0.05, 0.1 (on the die-sheet surface)

Therefore, a total of 72 ironing simulations were run. The rest of the process parameters were constant as follows:

- Punch speed: 5,080 mm/sec (400 SPM of 762 mm punch stroke)
- Die profile radius: 0.508 mm (the curvature at the curved-straight-curved die profile, as shown in Figure 2)
- Die throat length: 5.08 mm

### Results and Discussion of the Parametric Study for Ironing

To illustrate the effects of the process parameters in a more convenient way, the data obtained in the parametric study were processed and plots were prepared. Figure 7 illustrates the change in the maximum punch load with increasing punch-sheet friction coefficient ($\mu_1$) while keeping the die-sheet friction coefficient constant at 0.05.
The increase in the punch load for 20 percent and 27.5 percent reductions is not very significant; however, for 35 percent and 42.5 percent reductions, the punch load increases as $\mu_1$ increases.

Figure 8 illustrates the change in the maximum axial stress exerted on the cup walls with increasing punch-sheet friction coefficient ($\mu_1$) while keeping the die-sheet friction coefficient constant at 0.05. The increase in the punch load as a result of the increase in $\mu_1$ pays off in terms of the decrease in the axial stress that is exerted on the cup walls. Therefore, higher reductions can be achieved. Similar to the punch load, the sensitivity of the axial stress to $\mu_1$ increases as the percent reduction increases.

The die angle ($\alpha$, Figure 2) is a very important parameter in the ironing process. There is always an optimum die angle which would minimize the punch load. Figure 9 illustrates the change in the maximum punch load with increasing die angle for different reduction ratios and $\mu_1=\mu_1=0.05$. For 35 percent and 42.5 percent reductions, a 12.5-degree die angle results with lower punch loads, while that is not the case for 20 percent and 27.5 percent reductions.

The effect of the die angle on the axial stress is different than that on the punch load. The axial stress increases as the die angle increases (due to the increase in the redundant work and decrease in the punch-sheet friction).

**Temperature Predictions**

Due to the high speed of deformation, heat is generated during the operation. A total of eight nonisothermal (in other words, including heat generation and transfer) simulations with proper mesh on the dies were run to predict the temperatures during the operation. The effects of the following parameters were examined for a single pass ironing operation:

- **Punch speed:** 1.270, 2.540, 3.810, and 5.080 mm/sec
- **Thickness reduction:** 28 percent and 35 percent

Note that we were not able to find the proper thermal coefficients for AA3104-H19 aluminum for the nonisothermal simulations. Therefore, the data for AA1100-O was used:

- **Thermal conductivity ($\kappa_m$):** 0.022638 N·sec/C·x10$^8$
- **Heat capacity ($C_m$):** 2.0558 N·mm$^2$/C
- **Emmisivity ($\varepsilon_m$):** 0.0

Tool steel was selected as the die materials, and the heat transfer parameters were as follows:

- **Thermal conductivity ($\kappa_m$):** 0.0024575 N·sec/C·x10$^8$
- **Heat capacity ($C_m$):** 3.4767 N·mm$^2$/C
- **Emmisivity ($\varepsilon_m$):** 0.6

Initial temperatures of the dies and the sheet were selected to be 20 degrees C. Even though high temperatures (up to 155 degrees C) are reached in the sheet due to deformation, the major part of the die and the punch still stay at 20 degrees C. This is because of the high speed of the deformation which does not allow enough time for the heat transfer to occur.
This chart shows the maximum punch load with increasing die angle for different reduction ratios and $\mu_1 = \mu_2 = 0.05$.

Figure 9

However, this simulation can be regarded as the first production of the day where the tooling is cool. After 10 to 15 minutes, we may expect the tooling to get warmer and come closer to the temperature of the deformed sheet.

The maximum temperature reached in the sheet due to deformation increases as the speed of deformation and/or amount of deformation increases, as illustrated in Figure 10.

Figure 10

Conclusions and Future Work

Example simulations in this article are used to illustrate how computer-aided engineering (CAE) techniques can be used for the ironing process and tool design in can manufacturing. Although simulation times are currently quite extensive and are not suitable for practical design applications, with the developments in computer technology, CAE techniques will be used increasingly to reduce the process development time and tooling cost in the near future.

The application of drawing-redrawing-ironing processes for the manufacturing of beverage cans was examined in this work. Extensive simulations (parametric studies) of the ironing process with varying process parameters were conducted after the simulations of drawing and redrawing of AA 3104-H19 circular blank. An extensive literature review on the ironing process was also summarized. The two-dimensional FEM code DEFORM was used during the simulations. The findings can be summarized as follows:

1. The punch load and the axial stress exerted on the cup walls increase as the thickness reduction ratio increases.

2. The axial stress exerted on the cup walls decrease as the friction coefficient on the punch-sheet surface increases. Therefore, higher reduction ratios can be achieved. However, this increases the punch load, and may cause galling problems on the internal surface of the drawn cup.

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3. The axial stress and the punch load increase as the friction coefficient on the die-sheet surface, \( \mu_s \), increases, and the sensitivity of the punch load/axial stress to \( \mu_s \) increases with increasing thickness reduction.

4. There is an optimum die angle for every reduction ratio which minimizes the punch load, and this angle is not sensitive to the changes in the friction conditions (for the range of \( \mu_s = 0.05-0.15 \)).

5. The heat generated in the sheet due to deformation increases as the punch speed and/or the reduction ratio increases.

The effects of the punch speed on the flow stress of the sheet metal can be predicted if the flow stress of the sheet can be defined as a function of deformation speed. The stress distribution on the tooling can also be calculated.

The die and the punch can be meshed and specified as elastic materials so that the effects of elastic deflection of the workpiece and the tooling can be taken into account. Once a specific problem is defined, the other parameters can be fixed (such as the die angle, friction coefficients, etc.), which would save considerable amount of CPU time. Consequently, the redrawing and the subsequent three ironing operations can be simulated at once in a single punch stroke, which would be much closer to reality.

It should also be noted that most of the experimental studies were done with low punch speeds while the actual can manufacturing takes place with very high punch speeds. Therefore, the effect of higher punch speeds on the heat generation, and therefore the lubrication conditions, should be taken into account in the future studies.

In this work, Coulomb friction model was used with constant friction coefficients, which may not be very close to reality in the actual can manufacturing, where friction would be significantly influenced by the interface temperature.

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1. Brochure of the Stanum Company, Compton, CA.