Learning Module for using Dynaform® to Study the Effects of Die-Entry and Punch-Nose Radii on Drawing Cups

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Abstract

*The new model for an entry-level engineer in the United States automotive industry is that of a **design engineer**, one who is capable of part design and analysis using advanced CAE tools such as solid-modeling, mechanical systems dynamics (MSD), finite element analysis (FEA), and computational fluid dynamics (CFD). Since this will require a major change and enhancement of the current undergraduate engineering curriculum, the Mechanical Engineering Department at Kettering University (formerly GMI) is developing a comprehensive set of **Learning Modules** that can be woven into all Mechanical Engineering courses so that students use the tools often and in various contexts to solidify their knowledge of the computational tools and meet the learning objectives of the courses. The modules will be self-paced and self-explanatory, can be used by students and faculty outside of the classroom, and include meaningful examples that use CAE and existing laboratories to study real-life problems.*

*This paper describes one of the first **prototype** modules for Manufacturing and Mechanical Engineering students in a senior-level course in sheet metal forming. The students investigated the effects of changes in the die-entry radius and punch-nose radius versus depth of draw for cylindrical cups using various ring dies and flat bottom punches. The experimental data consistently showed that the die-entry radius has a very marked effect on depth while the punch-nose radius has very little effect. For a change in die-entry radius, once a minimum value has been exceeded, the material flows smoothly over the radius to generate a full depth cup.*

Simulation results using Dynaform® are presented that show that the experimental observations can be modeled by assigning appropriate values for the process parameters (die entry radius, clearance, friction, and binder). The Design of Experiments (DOE) method is used to develop guidelines for the selection of the process parameters for drawing cylindrical cups based on Forming Limit Diagrams from the simulations data.

Introduction

The automotive industry in the United States is changing its definition of the engineering job function. The new model for an entry-level automotive engineer is that of a ***design engineer***, one who is capable of part design and analysis using advanced Computer Aided Engineering (CAE) tools, such as solid-modeling, mechanical systems dynamics (MSD), finite element analysis (FEA), and computational fluid dynamics (CFD). Clearly this will require a major change and enhancement of the current undergraduate engineering curriculum.

The Mechanical Engineering Department at Kettering University (formerly GMI) is one of the largest producers of mechanical engineers in the nation and is committed to the integration of product design and realization into its undergraduate curriculum using modern industry-standard computational tools. This commitment is strengthened by Kettering's relationship with the automotive industry and being a 100% cooperative education institution.

As part of an on-going ***department-level reform***, a comprehensive set of ***learning modules*** are being developed that can be woven into all Mechanical Engineering courses so that students use the tools often and in various contexts to solidify their knowledge of the computational tools and (more importantly) to meet the learning objectives of the courses. The modules will be self-paced and self-explanatory so that they can be used by students outside of the classroom. They will include meaningful examples that use CAE to analyze real-life problems and existing laboratories to verify calculations.

The modules will be distributed to all faculty to help overcome their hesitation and fear about the integration of CAE in their courses. Many faculty indicate that they do not have enough time to cover the fundamentals and CAE tools, don't have time to learn the software, or are afraid of computers and change. The modules will allow faculty to learn on their own or they may choose to attend instructor-led training sessions.

Previous work has been done at Kettering in the area of sheet metal forming [Dev, S, 2002; Echempati, R., 2000; Echempati, R., 2002; Echempati, R., and Waldron, W.K., 2004], and CAE has been integrated into the SAE® Design Teams, e.g., SAE Formula, Mini-Baja, and Snowmobile Challenge [Hoff, C.J., et al. 2004]. This paper describes the development of one of the first ***prototype*** learning modules for Manufacturing and Mechanical Engineering students in a senior-level course in sheet metal forming. The objective of the learning module is to help the students understand the effects of changing process parameters using a method for Concurrent Product and Process Development [Echempati, R., and Waldron, W.K., 2004].

The students investigated the effects of changes in the die-entry radius and punch-nose radius on the depth of draw for cylindrical cups using various ring dies and 63.5-*mm* (2.50-*in*) outside diameter) flat bottom punches. The experimental data consistently showed that the die entry radius has a very marked effect on depth while the punch nose radius has very little effect. For a change in die entry radius, once a minimum value has been exceeded, the material flows smoothly over the radius to generate a full depth cup.

Simulation results using Dynaform® and LS-DYNA® are presented that show that the experimental observations above can be modeled by assigning appropriate values for the process parameters (die entry radius, clearance, friction, and binder). The Design of Experiments (DOE) method is used to develop guidelines for the selection of the process parameters for drawing cylindrical cups based on Forming Limit Diagrams (FLDs) from the simulations.

Importance of Concurrent Product and Process Development

Design is the process of converting information about the application into technical specifications for the product and its implied processes. It is an iterative activity that recognizes the goals or purposes of products or systems and creates and evaluates their form in accordance with the goals. It is also a dynamic evolutionary process.

The way in which products are produced has evolved during the last decade. Terms like Concurrent Engineering, Design for X, Life-cycle Engineering, and Lean Manufacturing have been used to indicate that an improved method was being implemented to design and manufacture products [Dixon, J.R. and Poli, C., 1995; Hundal, M.S., 1997; Magrab, E.B., 1997] Concurrent Product and Process Development involves the overlapping, interacting, and iterative nature of all the aspects that impact the product realization process. It is a continuous process that leads to a company’s increased profitability and market share based on a product’s cost, performance and features, value, and time-to-market [Thangaraj, R. et al., 1995].

Evolution toward Concurrent Product and Process Development in the United States was in part brought about by the realization that within the first 10% of the total time it will take to design, manufacture, and deliver a product, numerous decisions will have been made that effectively commit 85% of the funds to be expended for the project. However, during this short period of time less than 15% of these funds will actually be spent. In other words, the most influential decisions regarding the eventual expenditures for the product's introduction into the market will occur during the early stages of its development cycle. Thus, the cost of a change in the product at the final production run stage can be many times the cost of making the change at the design stage.

The overall goal of Concurrent Product and Process Development is to convert a product concept into a manufacturable, salable, and profitable product in such a way that the design of the product and the corresponding processes result in high customer satisfaction, short lead-times, high quality and reliability [Nevins, J.L. and Whitney, D.E., 1989]. This is accomplished by optimizing the product parameters and process parameters using CAE tools that are available today. In fact, many OEMs now require that their suppliers perform virtual simulations of the stamping process in order to reduce the more costly try-outs.

Laboratory Experiments

Laboratory experiments investigating the effects of "Changing Die-Entry Radius" and "Changing Punch-Nose Radius" were selected from Kettering's IME-404 (Sheet Metal Forming) course to illustrate the use of Concurrent Product and Process Engineering. The ***geometric parameters*** were the diameter of the cup (63.5 *mm*, 2.50 *in*), height of the cup (44.5 *mm*, 1.75 *in*), and blank thickness (0.762 *mm*, 0.030 *in*). The ***material parameters*** included the strain hardening exponent (n = 0.25), plastic modulus (K = 537 *MPa*, 78,000 *psi*) for *Cold-Rolled Drawn-Quality Aluminum-Killed* steel without a lubricant.

Figure 1 shows a schematic of the model with the basic definitions and parameters involved in a typical drawing operation for cylindrical cups. The ***process parameters*** include punch speed (305 *mm/s*, 60 *ft/min*), binder force (2.67 *kN*, 6000 *lb*), clearance (1.07 *mm*, 0.042 *in*) and static coefficient of friction between the tools ($\mu \sim 0.30$). A draw was considered successful if the cup did not fracture near the die-entry radius (chevron fracture, Figure 2) or the punch-nose radius. The latter failure looks like the top of the cup was punched out (Figure 3).

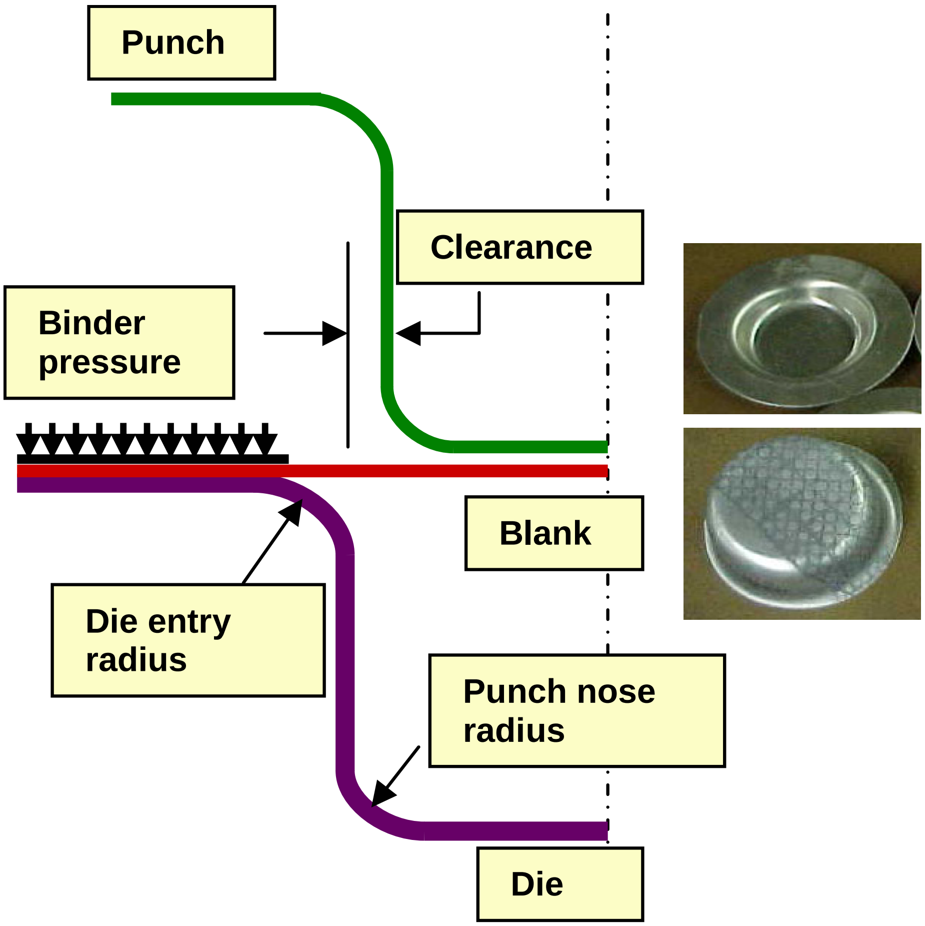

Figure 1 Schematic of the model for stamping design with process parameters

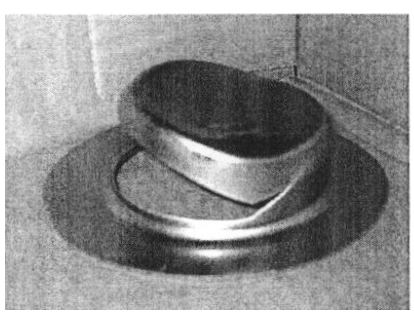

Figure 2 Die-entry radius failure

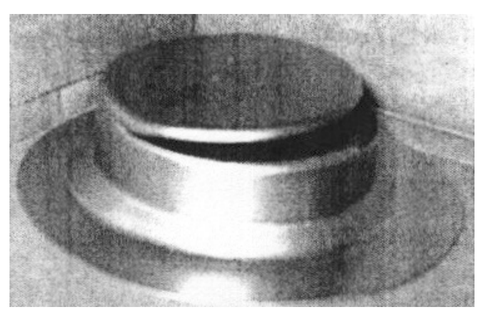

Figure 3 Punch-nose radius failure

The lines and square-shaped data labels in Figures 4 and 5 show the experimental results for the investigations into the effects of the die-entry and punch-nose radius on drawing cups. Figure 4 shows that with the 1.59 *mm* (0.063-*in*) punch-nose radius, full-depth draws of 44.45 *mm* (1.750 *in*) were achieved with the 3.175-*mm* (0.125-*in*) and 12.7-*mm* (0.500-*in*) die-entry radii but not the 1.59-*mm* (0.063-*in*) radius. The data in Figure 5 show that increasing the punch-nose radius was not sufficient to achieve a full draw with a 1.59-*mm* (0.063-*in*) die-entry radius, i.e., the die-entry radius has a very marked effect on depth while the punch nose radius has very little effect.

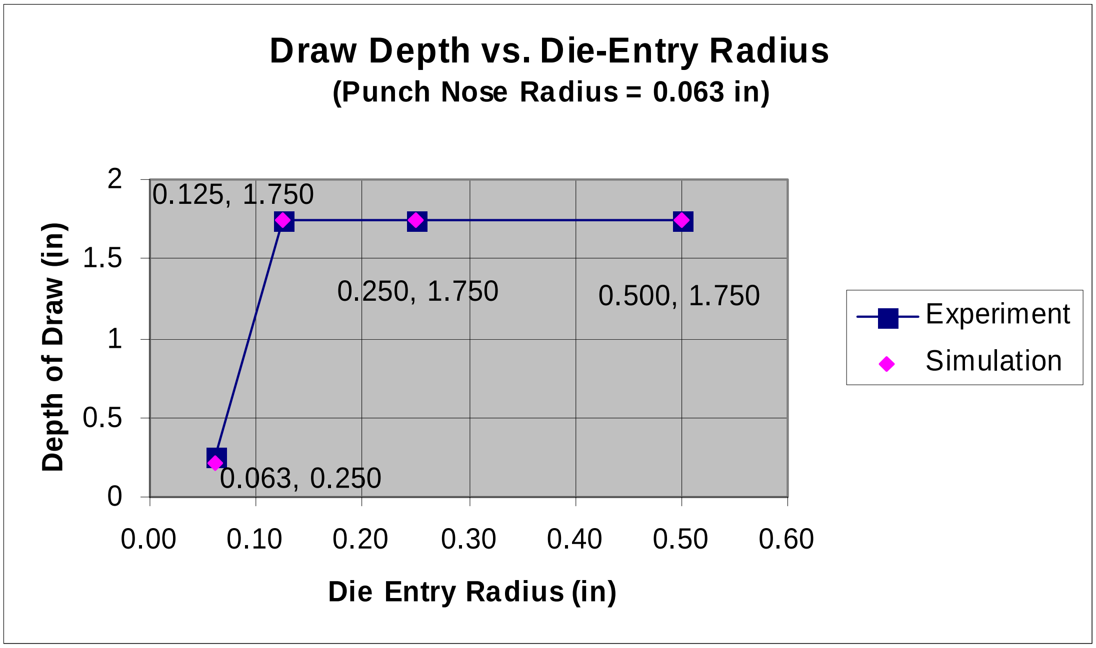

Figure 4 Effect of die-entry radius on draw depth

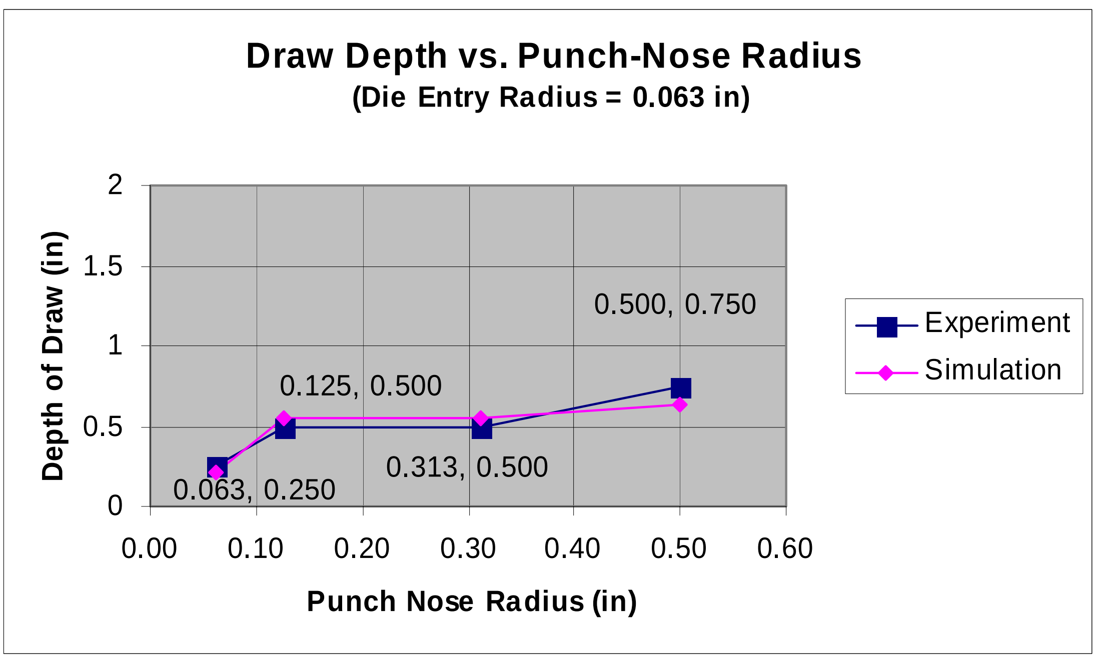

Figure 5 Effect of punch-nose radius on draw depth

Computer Simulations

In a typical product development cycle, the needs of the customers are translated into design criteria for the product (e.g., strength, weight, cost) followed by product and process specifications (e.g., material, geometry, and process parameters). CAE is a powerful tool for meeting design criteria, but its efficiency depends on the accuracy of simulation, which is complicated by the large number and interdependency of product and process parameters. The DOE method [Montgomery, D. C., 2000] was used to help select an initial set of process parameters to optimize the performance of a process or product.

Fitting the experimental data: Figure 6 shows a model that was made using a tutorial created by R. Echempati for using Dynaform® to simulate the drawing of a cylindrical cup. Only a quarter of the cup was modeled because anisotropy was neglected, and the cup was considered axially symmetric. The draw depth was determined by integrating the ***sinusoidal with hold*** velocity curve. The ***test*** case was the 3.175-*mm* (0.125-*in*) die-entry radius in Figure 4 because this was the minimum value for a full-depth draw with the 1.59 *mm* (0.063-*in*) punch-nose radius.

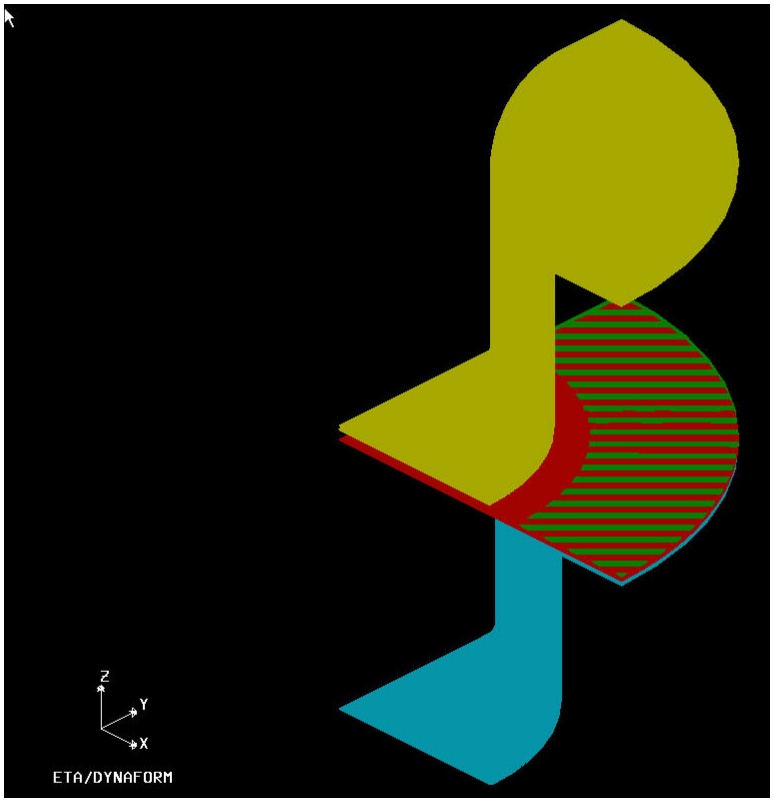

Figure 6 Model of tools to simulate the drawing of a cylindrical cup

Initially, trial and error was used to replicate the experimental result for the ***test*** case. Even with a priori knowledge of the process parameters used in the experiment, finding the right combination for a full-depth simulation was a time consuming process. After many iterations, a full-depth draw simulation was achieved using the parameters in Table 1. Note that all the simulation parameters were the same as used in the ***test case*** experiment for the 3.175-*mm* (0.125-*in*) die-entry radius, except for small changes in the binder force and clearance, along with significant changes in the coefficients of static friction between the blank and the binder and die.

Table 1 Comparison of process parameters used for experiment and simulation

Parameter	**Experiment**	**Simulation**
Thickness	0.03 *in* (0.762 *mm*)	0.03 *in* (.762 *mm*)
Clearance	0.042 *in* (1.07 *mm*)	0.043 *in* (1.10 *mm*)
Binder Force	6000 *lb* (26.7 *kN*)	5395 *lb* (24.0 *kN*)
Binder Friction	0.30	0.08
Die Friction	0.30	0.08
Punch Friction	0.30	0.30
Velocity	60 *fpm* (305 *mm/s*)	60 *fpm* (305 *mm/s*)
n	0.25	0.25
K	78 *ksi* (537 N/mm^2)	78 *ksi* (537 N/mm^2)

The diamond-shaped data labels in Figures 4 and 5 show the simulation results using the same process parameters as shown in Table 1. The simulation results compare favorably with the experimental data. This exhaustive exercise led to reasonably satisfying results and a better understanding of how the parameters affect the drawing process, but a DOE method was needed.

Design of Experiments: Figures 7 and 8 show the results from a DOE study using $L_4(2^3)$ orthogonal arrays (Table 2 and 3) [Taguchi, G. and Kanishi, S.] to investigate the ***influence*** and ***interaction*** of the die-entry radius with friction (Figure 7) and clearance (Figure 8). The process parameters were the same as shown in Table 1 except for a binder pressure of 26.7 *kN* (6000 *lb*) and changes in the clearance and friction. [Note that in the previous ***fitting the experimental data*** simulations, the value of the static coefficient of friction was μ = 0.30 for the punch, whereas it was 0.08 for the binder and die. For these and the remaining simulations, the value listed for the static coefficient of friction was applied to the binder, punch, and die.]

A clearance of 1.09 *mm* (0.043 *in*) was used for the four simulations in Figure 7. The results show that friction has a large ***influence*** on draw depth. Although using lubricants makes it difficult to maintain a clean and safe laboratory for the students, friction can be reduced using a lubricant. In order to help find an initial set of process parameters that result in a full-depth draw, the remaining simulations were done with μ = 0.20.

Since the slopes for μ = 0.08 and 0.30 are similar in Figure 7, there is little ***interaction*** between friction and die-entry radius. The data in Figure 8 with μ = 0.30 show that clearance has very little ***influence*** on the draw depth, and there is little ***interaction*** between clearance and die-entry radius.

Table 2 $L_4(2^3)$ orthogonal array to determine influence and interaction of the die-entry radius and friction with a clearance of 1.09 *mm* (0.043 *in*)

Run/Variable	1-der (*in*)	2-f	Depth (*in*)	Depth (*mm*)
1	0.125	0.08	1.40	35.5
2	0.125	0.30	0.23	5.86
3	0.500	0.08	1.71	43.4
4	0.500	0.30	0.37	9.27

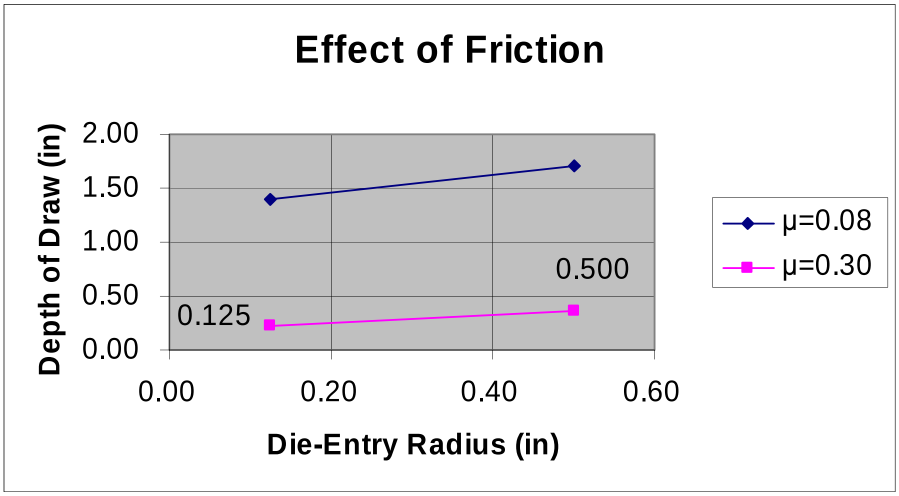

Figure 7 Influence and interaction of friction and die-entry radius

Table 3 $L_4(2^3)$ orthogonal array to determine influence and interaction of the die-entry radius and clearance with $\mu = 0.30$

Run/Variable	1-der (*in*)	2-c (*in*)	Depth (*in*)	Depth (*mm*)
1	0.125	0.040	0.23	5.92
2	0.125	0.046	0.22	5.57
3	0.500	0.040	0.37	9.35
4	0.500	0.046	0.36	9.19

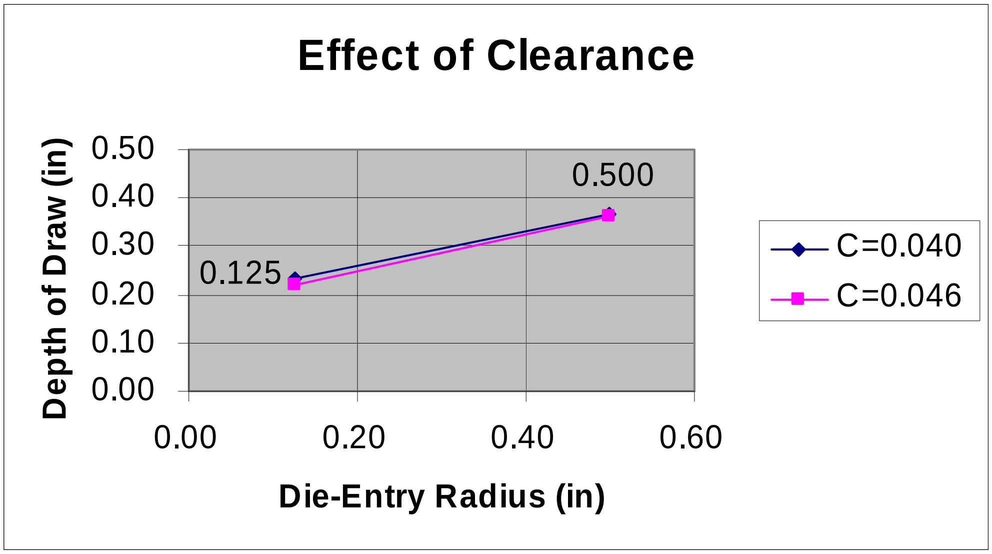

Figure 8 Influence and interaction of clearance and die-entry radius

The information above is useful, but a method was needed to select an initial set of process parameters before the tooling is designed and made. For this purpose, the $L_9(3^4)$ orthogonal array [Taguchi, G. and Kanishi, S.] in Table 4 was used to investigate the ***influence*** of the die-entry radius and binder force with $\mu = 0.20$ and a clearance of 1.09 *mm* (0.043 *in*). Figures 9 and 10 show the results of this DOE study. Inspection of the graphs leads to the selection of process parameters: 12.7-*mm* (0.500-*in*) die-entry radius and 2.67-*kN* (6000 *lb*) binder force. Run 9 used these parameters and resulted in a draw depth of 16.1 *mm* (0.63 *in*).

It might be troubling to some students that none of the simulations in the DOE studies predicted full-depth draws. The reason for this is that the presence of any (even one) strain states above the forming limit curves was considered a failure (see Figure 11). Students with experience using FEA software are familiar with results that include higher than expected stresses from highly distorted elements if the meshing was not sufficiently optimized. Convergence tests for the mesh were not done due to time considerations and the large number of simulations involved in the studies.

The simulation results are still useful even though they are consistently conservative. They allow the engineer to identify an initial set of process parameters before the tooling is made. In addition, the simulations help students understand the effects of the parameters on drawing cups.

Table 4 $L_9(3^4)$ orthogonal array to determine the influence of the die-entry radius, clearance, and binder force with $\mu = 0.20$

Run/Variable	1-der	2-c	3-b	Depth (*in*)	Depth (*mm*)
1	0.063	0.043	5000	0.26	6.7
2	0.063	0.043	6000	0.19	4.9
3	0.063	0.043	7000	0.19	4.9
4	0.125	0.043	6000	0.48	12.1
5	0.125	0.043	7000	0.40	10.3
6	0.125	0.043	5000	0.55	13.9
7	0.500	0.043	7000	0.55	13.9
8	0.500	0.043	5000	0.62	15.7
9	0.500	0.043	6000	0.63	16.1

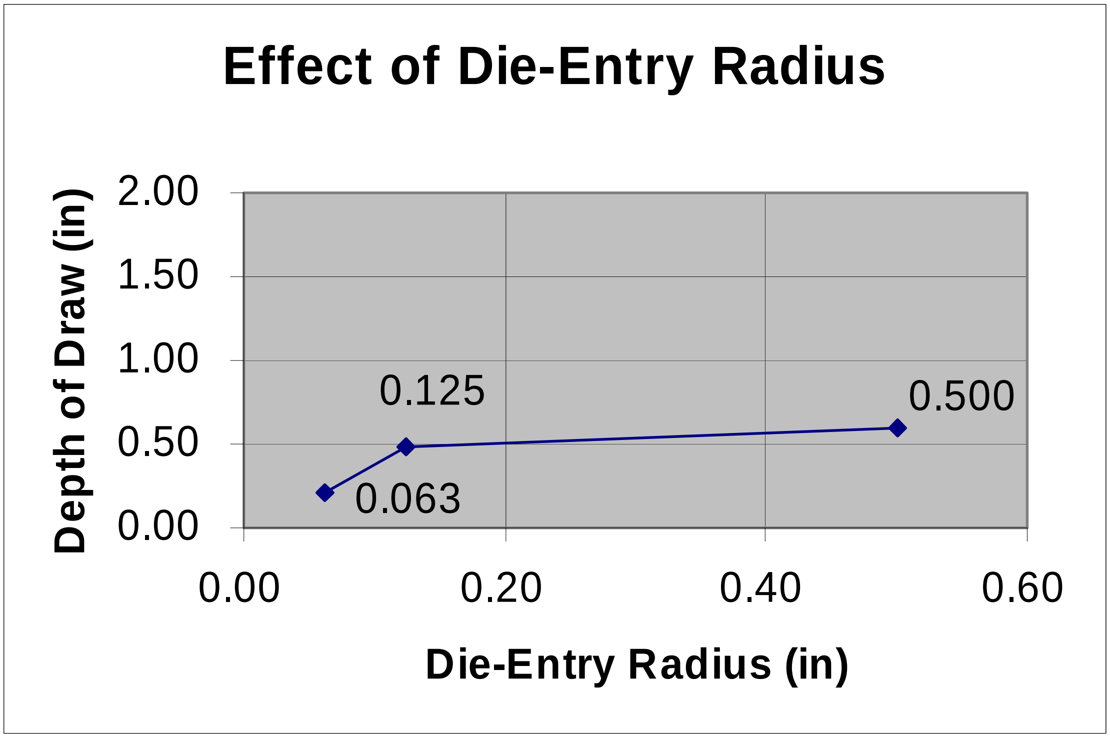

Figure 9 Influence of die-entry radius on draw depth

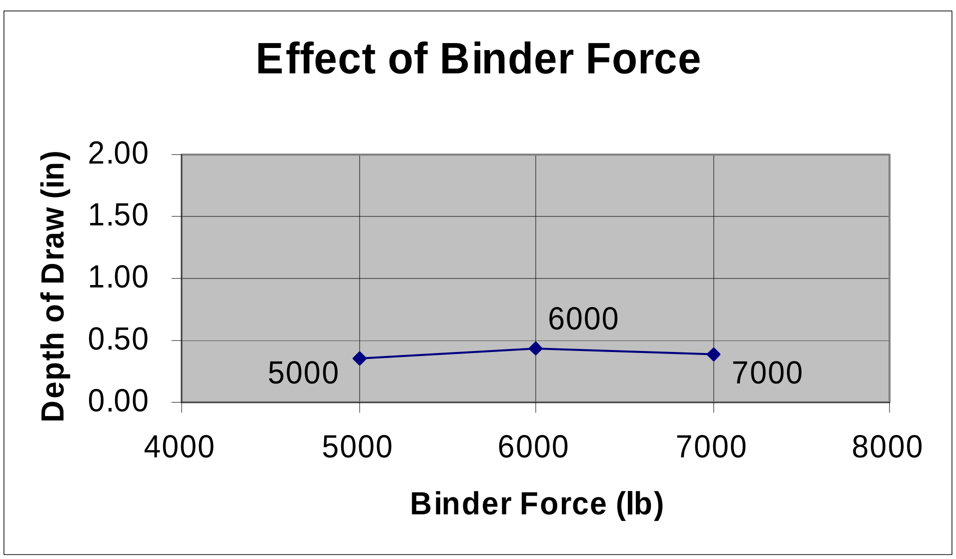

Figure 10 Influence of binder force on draw depth

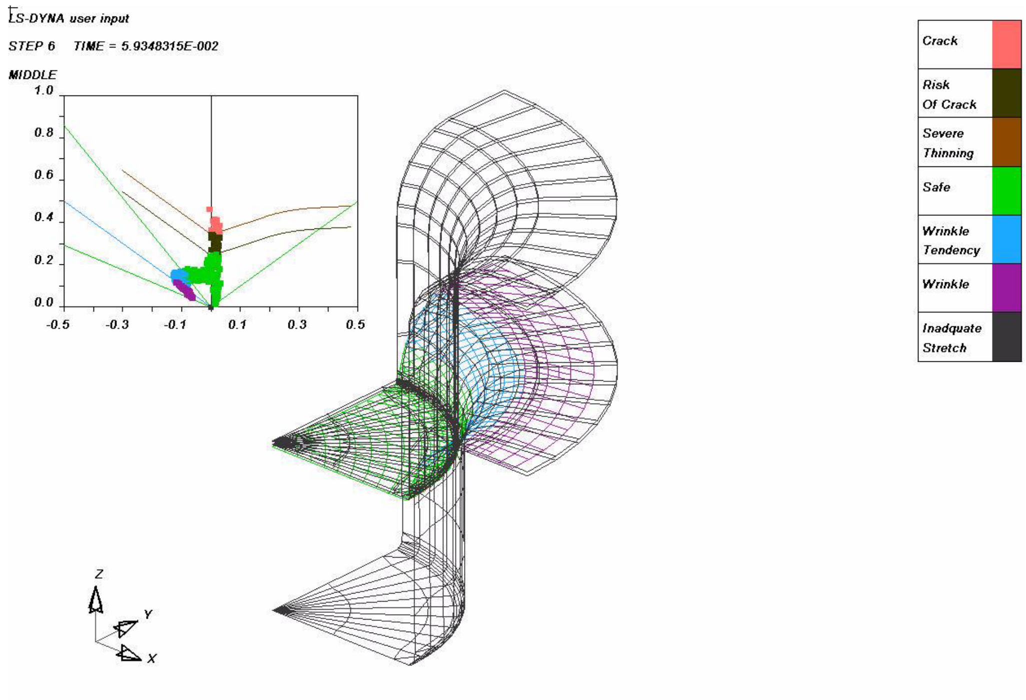

Figure 11 Forming Limit Diagram (FLD) from a Dynaform® simulation with a small number of strain states above the FLD curves

Learning Modules

It has been shown that the key to knowledge transfer is the amount of time devoted to acquiring skills within a domain [Bransford, J.D., et al., 2000]. As stated above, the plan is to weave the learning modules into all Mechanical Engineering courses so that students use the tools often and in various contexts to solidify their knowledge of the computational tools. The modules will be self-paced and self-explanatory for use outside of the classroom with examples that use CAE to analyze real-life problems and existing laboratories to verify calculations.

Besides the obvious emphasis on CAE technology, the modules will be developed for delivery using the University's Blackboard® course delivery system. Although the format of the learning modules needs to be developed, it is expected that they will be MS-PowerPoint® or HTML files that have been converted to Adobe® Acrobat (.pdf) files. In this way, a learning module can be placed in an instructor's Blackboard® course with links to the learning module's ***outline*** and its various components, e.g., background information on sheet metal forming, tutorial on creating simulations using Dynaform®, guide to solving the problem, and evaluating the results.

Conclusion

The development of a learning module was described for using a Concurrent Product and Process Development method to determine an initial set of process parameters for drawing cylindrical cups using simulations. A set of process parameters was found for a full-depth draw simulation that was consistent with the experimental results, but it involved a laborious trial and error method. DOE studies were undertaken to determine an initial set of process parameters a priori.

This work will be converted into ***learning modules*** that will help students learn to use Dynaform® and LS-DYNA® for metal forming analyses and improve their understanding of the ***influences*** and ***interactions*** of the process parameters.

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