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Aspects of Process Variables in Stamping Press Lines

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Abstract

This study investigates solving production problems in an automotive stamping plant using Finite Element (FE) analysis. The fundamentals of stamping, metal plasticity and FE analysis are developed. In this paper, we provide the basis for a simulation of the stamping of a production part, the automotive rear floorpan. On-plant factorial Design of Experiments (DoE) were simulated using the floorpan model. The accuracy of the simulations was undetermined because of variability in the DoE results. Predictions of flange shape, wrinkling and thickness show qualitative agreement with manufactured parts and indicate that simulating an industrial part is feasible.

Keywords : Design of experiments, Finite element, Metal stamping

1. Introduction

Stamping is a crucial manufacturing process that has played a major role in the mass production of cars. After Henry Ford started mass producing cars in the early 20th century the volume of stamped sheet metal rapidly increased. The process of stamping has been improved and refined in order to produce the large quantity of cars and variety of models that populate the world's roads and highways.

The metal stamping process converts a flat sheet of steel into the essential components of an automobile such as doors, fenders and bonnets. Yet manufacturing such commonplace components is still problematic. Stamping plant press down-time can exceed 50% and progress in eliminating production delays has lagged behind the demands of modern manufacturing which require quality and efficiency.

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Usually, each press line in a stamping plant produces multiple parts. The die-set, loaded into the press, determine which part is formed. Dies can be changed in production presses every eight hours or less, depending on the schedule. Our observations of a press shop are that delays typically occur after die-set changeover (Blumel et al, 1998). The following scenario demonstrates a normal post changeover problem observed at the plant. The new die-set is installed in the press, the press settings are adjusted according to the process control plan (PCP) and the resulting stamped part is defective. The tool makers then change press settings based on their intuition and feelings, depending on the type of defect. Trial and error adjustments continue until a good part is produced. Frustratingly the new press settings often finish being identical to the initial PCP, which failed the first time. There is no structured approach to solving changeover problems and the intuitive approach reveals a lack of understanding.

More problems often occur once the production appears stable. When a problem occurs, press operators continue stamping in the hope the problem will disappear. The floor between press lines becomes scattered with defective parts removed by the operator until finally, the scrap pile's height attracts attention. Then a tool maker is called over and the trial and error approach demonstrated above is used to rectify the problem. The lack of understanding of: the process, its control and the variations that occur are the reason stamping is described as an art rather than a science. In 'Fifty Years of Sheet metal Formability - Has Science Replaced the Art?' Keeler (1988) concludes stamping is till an art controlled by instinct and problems appear to be solved by magic. The goal of this study is to investigate the use of Finite Element (FE) computer simulations of sheet metal forming to solve production problems.

2. The Fundamentals of Stamping

Stamping must be understood in order to simulate it. Yet the shop floor workers, who run the press in the plant, describe the process as a black box. They are aware of the interactive nature of all the variables that can effect the production of parts. However the complexity of the interactions is so overwhelming they attach mystical properties to them and call stamping a black box process to account for their gaps in understanding.

2.1 Sheet Metal Forming

The rear floorpan is produced by the specific sheet forming process of deep-drawing. Due to the floorpan's large size, it is made in the heavy press shop on a double action mechanical press. Routine problems during production occur from instability in process variables. The cause of a problem must be known to rectify it so monitoring the process variables is important. Solving problems also requires control of process variables.

Deep-Drawing: deep-drawing is the process of forming a deeply shaped part from a flat sheet of metal. The classic example of deep-drawing is stamping an axisymmetric cup from a circular sheet of steel. The rear floorpan is a real deep-drawing problem, strikingly similar in form to the circular cup, with the complication of starting from a rectangular blank. The sheet metal or blank is placed on top of the die and compressed by the blank holder. The punch presses the blank into the die cavity and forms the part. The outer edges of the blank which are not drawn into the die cavity are called the flanges. The most important control input to deep-drawing is the force applied through the blank holder to the flanges (Traversin & Kergen, 1995). The blank holder force provides the subtle balance between drawing and stretching, wrinkling and splitting, which is deep-drawing. The restraining force experienced by the blank depends on the contact interaction between the blank and blank holder. Friction and lubrication are vital in stamping. Ko (2006) tried to stamp the floorpan without lubricant with disastrous results. The part became wedged in the die and took 30 minutes to remove. Besides production delays, the tooling is costly and damage is to be avoided.

Drawbeads: A flat blank holder means the restraining force is constant over the entire flange. The restraining force is directly proportional to the blank holder force and the lubrication. Both must be controlled precisely for repeatability. A drawbead has a small radius ridge on the die and a mating recess in the blank holder. When the blank holder is closed the blank is forced to conform to the shape of the drawbead. During drawing, the blank must be pulled through the drawbead. Significant force is needed to bend the blank over the severe shape of the drawbead. This force, combined with higher friction, increases the restraining force. The drawbead has additional benefits. Much of the restraining force provided by the drawbead comes from the flange bending and unbending. Restraining force is dependent on drawbead geometry not blank holder force. Therefore large restraining forces can be generated on smaller presses without sensitivity to blank holder force. This type of decreased sensitivity to process variation is essential to stamping.

Tonnage: Debates on the shop floor as to whether tonnage is an input or an output are similar to debates on politics or football. People have set different opinions and benefits. Digital gauges on the press reveal the tonnage in the four corners of the blank holder and the punch after each part is stamped. Yet it is impossible to turn a dial and get 47 tons in the front left corner of the blank holder. You can change shut height or corner pressure which will influence the tonnage but tonnage is not a direct input. The tonnage is irrelevant if the stamped panel contains no splits or wrinkles and can be assembled. So tonnage is neither an input nor output, tonnage is a process variable.

Process Variation: If there was no variation in stamping then delays would never occur during production. Production delays occur daily but the source of the variations is often mysterious. Perhaps the steel quality is varying or the die is worn. Determination of the source would then allow adoption of a strategy for eliminating the variation. Poor quality steel could be returned to the supplier or the worn die resurfaced. Part quality could be even more robust to an inherently unstable press.

Culture and Control: Stamping plants have been making cars for a century and will continue to do so but Keeler (1978) says that stamping operations must improve because of a loss of knowledge and changing business practices which demand efficiency. Organizational knowledge in a stamping plant resides within the minds of the employees (Harrison, 1990). They solve problems intuitively so there is no documented way of learning. Knowledge comes from years of practical experience. Down-sizing of operations reduces the intake of craft and technical apprentices and those that do qualify for employment tend to be more mobile in their careers. The employees of a stamping plant are a vital asset because loss of employees correlates with loss of knowledge.

Process Optimization for Robustness to Variation: Nolan (1997) correlates the results of three on-plant experimental studies that attempt to use factorial experiments on problematic parts to optimize the process settings for robustness against variation. He found that simple factorial DoE using one, two or three levels have proven to significantly reduce scrap. Factorial DoE are successful because they take a logical approach to problem solving in contrast to the trial and error approaches that press operators often use. A disadvantage to DoE is that the results are part specific so must be repeated on all problem parts. Repeated experiments require time on production presses which is difficult to obtain. Nolan (1997) observed that blank holder force, called binder pressure, is the most important variable used in DoE work. He suggests that doing one factor experiments and only varying blank holder force may be the most efficient method of optimizing stamping. This is a logical extension of Siekirk‘s (1986) control strategy. Ko's factorial experiments used the press settings that have the most effect on blank holder force: shut height and corner pressure. He also varied blank position on the die. Siekirk (1986) found that blank position is important and for the quarter panel he studied variations of 1/16 of an inch had a significant effect on strain.

2.2 Deformation and Friction

Sheet metal forming changes a flat sheet of steel into a useful part by bending, stretching and straining the metal into a new shape. Plasticity theories are mathematical descriptions of experimentally observed deformation which are embodied in FE codes. The fundamentals of deformation theory must be understood to use the codes correctly. This section is to give a practical user of FE codes understanding of metal plasticity to undertake forming analysis. For further detail see Hill (1950) who pioneered the theory of metal plasticity, Zienkiewicz (1994) who approaches deformation from a continuum mechanics perspective for FE analysis or Hinton (1992) who discusses material properties specifically for application to FE software.

2.3 Finite Element Analysis

The Finite Element method is a mathematical technique which can solve a wide range of engineering problems. The method is complicated and embodied in software so the analyst can concentrate on simulating their application rather than implementing mathematics. ABAQUS is a commercial FE software used to simulate the stamping of the floorpan. Running an ABAQUS simulation does not require a rigorous understanding of the FE method, however the fundamentals must be grasped because ABAQUS is a powerful code with very little error checking. This means ABAQUS will easily solve problems even though they are physically impossible. Practical knowledge of using FE codes is essential to building an accurate and efficient model.

3. Model Development

The goal of this study is to solve production problems in stamping using finite element simulations. An accurate FE model of stamping must be built and validated before it can be used with confidence to solve problems. Ko's factorial design of experiments work on the rear floorpan was done to optimize the press settings against process variation. FE simulation of a series of Ko's experiment will test both the simulations accuracy and the validity of optimization on the computer.

3.1 Geometry

As the name suggests, finite elements are the heart of FE modeling. The quality of the mesh directly affects the quality of the results. Developing a quality mesh requires skillful engineering judgment. A fine mesh more closely represents the real structure and gives more accurate results but large models are prohibitively expensive on computer resources. There is an ongoing trade-off between result accuracy and cost in large nonlinear simulations as sheet metal forming.

Selection of Element Type: ABAQUS has vast element library. Choosing the best element for an application depends on the geometry and expected deformation, balanced against the accuracy and cost of the solution. Elements have specific applications so using an appropriate element will allow a simpler mesh that gives fast, accurate solutions. If a beam can be modeled using simple and fast 2D beam elements it is pointless using slow 3D continuum elements.

Mesh Density: The art of using the finite element method lies in choosing the correct mesh density required to solve a problem (Hinton, 1992). The FE method calculates the solution at the nodes and interpolation functions approximate the solution through the interior of each element. Elements are most accurate when they have an aspect ration (the ration of an element's width to height) of 1, the strain and strain gradients across the element are small and the distortion is minimal. Simplistically, using a huge number of elements would give the best solutions but that is not practical or entirely true.

3.2 Material Properties

Metal Plasticity: ABAQUS's metal plasticity model incorporates the important features of plasticity theory, that is: elastic-plastic model with an isotropic plastic yield using Hill's yield function and isotropic hardening.

Friction: Coulomb's law with a shear stress limit is the only friction model in ABAQUS. No experimental apparatus was available to measure the coefficient of friction so a coefficient was estimated from the experimental work (Nine, 1982). Nine (1982) determined the coefficient of friction ranged from 0.06 to 0.18 depending on variation in steel type, sheet thickness, lubricant and contact pressure.

3.3 Loading

The double action press moves the punch and blank holder to control the deep-drawing of the floorpan. To simulate the press, boundary conditions are applied to the rigid surface meshes of the punch and blank holder.

Punch Velocity: The floorpan's wheel well is 205mm deep. Therefore the punch must move 205mm vertically to stamp a floorpan. The punch's motion is simulated by a velocity boundary condition. The velocity is applied for the time required for the punch to move 205mm. The appropriate time depends on the velocity. Increasing the velocity decreases the time which also decreases the solution time.

Blank Holder Force: Although similar inputs (shut height and corner pressure) control the blank holder and the punch their effect is different. The punch does not push the blank directly against the lower die. Therefore, changing the shut height gauge does change the punch's position at bottom dead center. The blank holder pushes the blank against the lower die to impart a restraining force. Lowering the blank holder's shut height increases the blank holder force but does not lower the blank holder's position.

4. Experimental Validation

The floorpan simulation model must be accurate if it is to solve production problems. On-plant experimental work specifically for validating the floorpan simulation was outside the scope of this paper. However, Ko did a parallel research involving on-plant factorial design of experiments on the rear floorpan. His experimental data for stamping of the floorpan on production presses was used for comparison.

4.1 Analysis of On-Plant DoE

Ko's goal was to optimize process settings to make part quality more robust to variation using DoE. His experiments were not designed for validating an FE model. This section describes his experiments and analyses their suitability for validating the accuracy of the FE floorpan model.

Inputs: The concept of factorial experiments is simple. Choose the inputs or factors and their values or levels then conduct experiments at all input combinations. In general the number of experiments e depends on the number of inputs i and the number of levels l by:

$$e = l^{i} \tag{1.1}$$

Equation 1.1 shows that the number of experiments is sensitive to the number of input factors.

Time for on-plant experimentation was severely restricted so Ko had the difficult task of culling the many possible process variables. Additionally the inputs must be controllable, observable and have a significant interaction with the output part quality parameters whose variance stops production. Delays were usually because of flange length variations on the floorpan which cause assembly difficulties.

Siekirk's (1988) control strategy identified blank holder force as the best single control to accommodate production variation. However blank holder force is not an input, therefore blank holder shut height was the first most logical input to use because it has the most effect on blank holder force.

Corner pressures where not varied for the experiments but significantly they where uneven. Flange draw is sensitive to corner pressures so corner pressures are commonly adjusted to fix flange length problems. Therefore uneven corner pressures are significant but quantifying the effect is impossible.

Outputs: Flanges do not draw in evenly. Therefore flange length is a continuous function of position. Measuring the flange length requires a frame of reference. Ko measured flange length at one position on each of the four flanges. Each floorpan was placed on a custom built jig and the flange lengths were read off metal rulers fastened to the jig. Ko's flange lengths have no direct correlation with the length of a flange.

4.2 Comparison Between FE and DoE

Ko's two factor (shut height and blank position) three level experiments required parts to be stamped at the nine possible combinations of the input factors. At each of the nine combinations three consecutive floorpans were stamped. The flange lengths were measured at each of the four flanges. There was a significant variation in the flange lengths between the three parts stamped with the same shut height and blank position According to the FE simulation results, the front and rear flanges are longer than the DoE, while the left and right flanges are shorter. The same general trends can be observed as the blank position and shut height are changed but the large experimental variation casts doubt on the comparison.

4.3 Qualitative Predictions

With the assumptions incorporated in the floorpan model and variable experimental results, it is unsurprising that the accuracy of the floorpan model could not be validated. The experimental and simulation difficulties highlight how complicated and challenging it is doing research on an industrial manufacturing process compared to simulating well controlled laboratory experiments. However the floorpan model is capable of simulating the floorpan. The simulation makes qualitative predictions of flange shape, wrinkling and thickness. With improved experimental measurements and modeling techniques, the floorpan model should be capable of producing accurate results as well.

5. Conclusions

Solving production problems in the stamping plant requires consideration of the total stamping process. Accurate FE simulations of the metal deformation alone will not solve production problems. As previously discussed, the stamping process is composed of two separate systems, the press and the part. Only the part system can be modeled with FE analysis. Therefore, the press remains unaccounted for even though it controls the stamping process. In conclusion, the stamping process is a complex interactive system. Stamping combines the press, tools, sheet metal and deformation which must all be considered in an overall system to solve production problems using FE simulations.

References

1. Blumel, K., Hartmann, G. and Lubeck, P. (1998). Variations of the Stamping Process, In 15th IDDRG Biennial Congress, International Deep Drawing Research Group, 9-16.
2. Hill, R. (1950). *The Mathematical Theory of Plasticity*, Oxford University Press.
3. Hinton, E. (1992). NAFEMS Introduction to Nonlinear Finite Element Analysis, NAFEMS, Glasgow.
4. Harrison, T. L. (1990). Building Core Competencies in Auto Body Panel Stamping through Computer Simulation, Master's Thesis, Massachusetts Institute of Technology.
5. Keeler, S. P. (1978). Mechanics of Sheet Metal Forming, chapter Sheet Metal Stamping Technology - need for Fundamental Understanding, Koistenen D. P. and Wang, N. (Eds.), 3-18.
6. Keeler, S. P. (1988). Fifty Years of Sheet Metal Formability - Has Science Replaced Art?, SAE Technical Paper, 27-34.
7. Ko, J. (2006). Improving Process Stability Using Design of Experiments, *Journal of Korean Data & Information Science Society*, 13(2), 129-137.
8. Nine, H. (1982). The Applicability of Coulomb's Friction Law to Drawbeads in Sheet Metal Forming, *Journal of Applied Metal Working*, *2*(3), 200-210.
9. Nolan, M. T. (1997). The Use of Process Control in Sheet Metal Stamping to Create Robustness to Material Variation, Master's Thesis, Massachusetts Institute of Technology.
10. Siekirk, J. F. (1986). Process Variable Effects on Sheet Metal Quality, *Journal of Applied Metal Working*, *4*(3), 262-269.
11. Siekirk, J. F. (1988). A Systems Approach to Sheet Metal Forming Process Control, In 15th IDDRG Biennial Congress, International Deep Drawing Research Group, 1-7.
12. Traversin, M. and Kergen, R. (1995). Closed-loop Control of the Blank-holder Force in Deep-drawing: Finite-element Modeling of Its Effects and Advantages, *Journal of Materials Processing Technology*, 50, 306-317.
13. Zienkiewicz, O. C. and Taylor, R. L. (1994). *The Finite Element Method*, McGraw-Hill, New York.

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